AD-A144 388 ABSTRACTS ON THE INTERNATIONAL CONFERENCE ON NOISE IN PHYSICAL SYSTEMS (7..(U) MONTPELLIER-2 UNIV (FRANCE) 20 MAY 83 1/5

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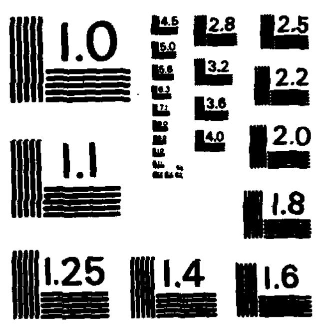

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PROGRAM

	TUESDAY 17		WEDNESDAY 18		THURSDAY 19		FRIDAY 20	
	ROOM A	ROOM B	ROOM A	ROOM B	ROOM A	ROOM B	ROOM A	ROOM B
8.30	Opening ses.		I.P. Clarke		I.P Gagnepain		I.P van d.Ziel	
9	I.P Van Vliet		I.P. Suzuki		I.P Vandamme			Noise in other physical systems
10	I.P Libchaber		Theory 1/f noise	Quantum noise	1/f noise in resistors and thin films		1/f noise in diodes	
	Theory	1/f noise in bipolar transistors						
11								
								Noise in other physic systems
12	Theory	1/f noise in bipolar transistors	Theory 1/f noise	Quantum noise	1/f noise in resistor and thin films	Oscillators	1/f noise in diodes	
13								
14.30	I.P Moss		I.P Boussart				I.P.Nougier	
15	I.P Lefever		Metrology	Theory 1/f noise			Hot carriers and submicr. devices	1/f noise in diodes
16								1/f noise in resistors & thin films
17	Theory	1/f noise in FET transistors	Noise in diodes and transistors	1/f noise in physical and chemical systems			Hot carriers and submicr. devices	
18							Closing addr.	

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T U E S D A Y   M O R N I N G

ROOM A

L1

Invited Paper

FLUCTUATIONS AROUND A NON-EQUILIBRIUM STATE

Pr. C.M. VAN VLIET

Department of Electrical Engineering
University of Florida and

Centre de Recherches de Mathématiques Appliquées
Université de Montréal

This talk will be divided into two parts. First, we address the problem of the form for thermal noise in a driven, non-equilibrium state, sufficiently close to thermal equilibrium, in a non-linear device. In such a system the Hamiltonian is divised into three parts, $H = H_\phi + H_L + H_2$, H_ϕ is the system Hamiltonian, H_L the coupling to a thermal bath, and H_2 the coupling to an external field.

In a non-equilibrium state the noise is due to the energy contained in H_L as well as in H_2, so that one cannot properly distinguish between what is traditionally called thermal noise and shot noise. A thermodynamic generalized entropy form (Massieu function) is derived from H_L and H_2, leading to Gupta's result for the noise in a non-linear driven state. As nonlinear device examples, we consider p-n junctions and tunnel diodes, and we derive from Gupta's result the well known shot noise and thermal noise formulas for these devices. The result will also be compared with propositions concerning nonlinear device noise given by van der Ziel.

Secondly, we consider a non-equilibrium Markov-Langevin formulation, due to Lax (1960, Revs of Mod. Phys.), Van Vliet (1965, Fluct. Phenomena in Solids ; 1966, Phys. Rev. ; 1971, J. Math.Phys.) and Tremblay et Al. (1980, Phys. Lett.). The main result for Markov systems is contained in the generalized Einstein relation, first derived by Van Vliet and Blok (1956, Physica) : Covar (AA)M + $\tilde{M}$ Covar (AA) = 1/2 S = D, where A means the fluctuating variables, M is the linearized regression tensor, and where S is the spectrum of the Langevin forces while D is the generalized

[redacted]

diffusion tensor. In thermal equilibrium both terms on the left-hand-side are equal and Covar (AA) takes the thermal equilibrium form $1/4\ M^{-1}\ S$, which can be related to the inverse second order entropy derivative tensor. There is a small problem with magnetic field reversal, not hitherto correctly considered in the literature, which will be discussed. Outside thermal equilibrium the full generalized Einstein theorem is required and considerable changes can occur. This is first illustrated for a photoconductor driven by a strong optical pump (Van Vliet, 1966). Carrier density noise, with a strong super - Poisson character can be observed. Next, we consider the Brillouin light scattering in a fluid with a small temperature gradient (Tremblay et Al. 1980). Their treatment is shown to be a particular case of the general formalism considered by Van Vliet (1971). Solving the generalized Einstein equation for this case and following Tremblay et Al., the asymmetry of the Brillouin peaks is obtained and explained.

As is noted, the two parts of this talk are disjoint. It is conjectured that a connection could be fruitfully obtained if the recent linear response theory formulation by the author and coworkers (J.Math. Phys. 1978, 1979, 1982) could be extended to derive a fluctuation - dissipation theorem as well as a generalized Einstein formula in the presence of a field, using a generalized canonical density operator for the driven n equilibrium state. Such an extension is being contemplated, but has not yet been carried out.

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Invited Paper

NOISE IN CHAOTIC FLUID SYSTEMS

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We illustrate, in a Rayleigh - Benard experiment, the various types of noise appearing in dynamical systems. Intermittent noise, power law spectrum, exponential noise may appear depending on the scenario leading to a chaotic behavior.

References :

1. J.P. Eckmann, Rev. Mod. Physics 53, 643 (1981)
2. A. Libchaber, S. Fauve, "melting, localization, chaos", Kalia and Vashishta Ed., Elsevier 1982.

THEORY

[redacted]

A new transform theorem linking spectral density and Allan variance.

C.M. Van Vliet, University of Florida, Gainesville, and Université de Montréal, Canada, and P.H. Handel, University of Missouri at St. Louis.

It is well known that neither the Wiener-Khintchine theorem, nor MacDonald's or Milatz's theorem, can handle 1/f noise or "more pathological" noises, since the correlation function as well as the variance of the integrated time-dependent average, necessary for these theorems, diverge. Thus, via these theorems no time domain description of 1/f noise can be obtained. The situation improves, however, if use is made of the Allan variance, defined as follows. Let m(t) be the stochastic variable, e.g., an emission rate. Let $M_T^{(1)}$ and $M_T^{(2)}$ be defined as the time integral in adjacent time intervals $(t, t+T)$ and $(t+T, t+2T)$. The Allan variance $\left(\sigma^A_{M_T}\right)^2$ is then defined as

$$\left(\sigma^A_{M_T}\right)^2 = \frac{1}{2} < \left(M_T^{(1)} - M_T^{(2)} \right)^2 > , \tag{1}$$

where the angular brackets denote an ensemble average over a sufficient number of adjacent time intervals. Note that for emission phenomena $\left(\sigma^A_{M_T}\right)^2$ is easily measured by counting techniques. This Allan variance (time domain) is then linked to the spectrum $S_m(\omega)$ of $<\Delta m^2>$ by the "Allan variance theorem" proven by the authors[1]:

$$\left(\sigma^A_{M_T}\right)^2 = \frac{4}{\pi} \int_0^\infty \frac{d\omega}{\omega^2} S_m(\omega) \sin^4\left(\frac{\omega T}{2}\right) . \tag{2}$$

The inversion of the theorem proved to be an interesting problem in the theory of Fredholm integral equations[2]; it reads for the simplest case that a consecutive Mellin-Laplace transform of the Allan variance exists:

$$S(\omega) = -\frac{1}{2\pi i} \int_{-i\infty+\beta}^{i\infty+\beta} \frac{dp}{\omega^{p-2}} \frac{\cos \frac{1}{2}p\pi}{1-2^{p-3}} \Gamma(p) \int_0^\infty \frac{dT}{T^p} \left[\sigma^A_{M_T}(T)\right]^2 . \tag{3}$$

Here β is in the domain of analyticity of $\Gamma(p) \int_0^\infty dT\, T^{-p} \left(\sigma^A_{M_T}\right)^2$. If only partial Mellin transforms exist, more complex formulas apply. In the table below we give the transform pairs [and F(s) which is the Laplace transform of the Allan variance] for white noise, Lorentzian noise, and "pathological noises." It is seen that $\left(\sigma^A_{M_T}\right)^2$ usually exists! (i.e., is convergent for all T).

	$S_m(\omega)$	$F(s)$	$\sigma^{A2}_{M_T}(T)$
Poissonian shot noise	$2m_0$	$2m_0/s^2$	$\langle M_T \rangle = m_0 T$
General shot noise	$2\langle \Delta m_T^2 \rangle T$	$2\langle \Delta m_T^2 \rangle T/s^2$	$\langle \Delta M_T^2 \rangle = \kappa m_0 T$
1/f noise	$2\pi C/\lvert\omega\rvert$	$4C(\log 2)/s^3$	$2CT^2 \log 2$
Lorentzian flicker noise	$4B \dfrac{\alpha}{\alpha^2+\omega^2}$	$2B\left[\dfrac{4\alpha}{s^2(s^2-4\alpha^2)} - \dfrac{2\alpha}{s^2(s^2-\alpha^2)} - \dfrac{6\alpha^2}{s(s^2-4\alpha^2)(s^2-\alpha^2)}\right]$	$\dfrac{B}{\alpha^2}[4e^{-\alpha T} - e^{-2\alpha T} + 2\alpha T - 3]$
"Pathological noise"	$L/\lvert\omega\rvert^{\lambda-1}$ $0 < \lambda < 4;\ \lambda \neq 2$	$\dfrac{L(1-2^{\lambda-2})s^{-\lambda-1}}{\sin(\pi\lambda/2)}$	$\dfrac{LT^\lambda(1-2^{\lambda-2})}{\sin(\pi\lambda/2)\Gamma(\lambda+1)}$

In counting experiments involving Poissonian shot noise, $S_m(\omega) = 2m_0$, and 1/f noise, $S_m(\omega) = 2\pi C\, m_0^2/\omega$, the relative Allan variance is given by

$$R(T) = \frac{\left\langle \left(M_T^{(1)} - M_T^{(2)}\right)^2 \right\rangle}{2 \langle M_T \rangle^2} = \frac{1}{m_0 T} + 2C \log 2\ . \tag{4}$$

For $T \to \infty$, $R(T) \to 2C \log 2$, the so-called flicker floor. Thus a measurement of R(T) as a function of T gives the magnitude of the 1/f noise. This important result is applied in a subsequent paper to determine the 1/f noise inherent in α-particle emission.

1) C.M. Van Vliet and P. Handel, Physica 113A, 261-276 (1982).

2) C.M. Van Vliet, Annales des Sciences Mathématiques du Québec, in press.

L 1

STOCHASTIC MODEL OF THE BURST NOISE

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In this paper it is assumed that the burst noise is induced by a *primary process* $X(t)$ which is represented by capturing or emission of a carrier by a trap which controls the current through the defect. The *secondary process* $Y(t)$ is then represented by the current modulation. For a three-state primary process $X(t)$ from the Kolmogorov's equations the absolute distributions and the transition probabilities of the $X(t)$ and $Y(t)$ processes are derived. The correlation function of the secondary process $Y(t)$ is then

$$B_Y(t) = A_1 . e^{\alpha_1 t} + A_2 . e^{\alpha_2 t} \quad , \quad \text{for } t > 0 \, , \tag{1}$$

where A_1, A_2 are quantities determined by the transition intensities, α_1, α_2 are the eigenvalues of the intensity matrix.

The *spectral density of the* $Y(t)$ process is a superposition of two one-dimensional generation-recombination processes:

$$S_Y(\omega) = \frac{A_3}{(\alpha_1^2 + \omega^2)} + \frac{A_4}{(\alpha_1^2 + \omega^2)} \quad ; \tag{2}$$

where the coefficients A_3, A_4 are determined by the transition intensities.

A particular case where the carries make transitions between the trap and the valence or conductivity band is discussed. Interband transitions are assumed to have zero intensity.

Experimental study of the temperature dependence of the spectral density and the amplitude distribution of the noise voltage is described. In a simplified case the current fluctuation spectral density $S_i(\omega)$ can be expressed in the form

$$S_i(\omega) = \frac{I_{BN}^2}{2\pi} \cdot \frac{1}{1 + \cosh(E_t - E_{Fn})/kT} \cdot \frac{\tau}{1 + \omega^2 \tau^2} \tag{3}$$

where I_{BN} is the burst noise current amplitude, E_t and E_{Fn} are the trap and quasi-Fermi energy, respectively, τ is the effective relaxation time.

MICROSCOPIC SPATIAL CORRELATIONS

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The noise of devices is due to local noise sources, the effect of which at the electrodes is taken into account through the impedance field. Usually, the noise sources at two different points $\vec{r}$ and $\vec{r}'$ are supposed to be uncorrelated, thus giving $S_{\Delta j}(\vec{r}, \vec{r}', f) = K(\vec{r}, f)\delta(\vec{r} - \vec{r}')$ where $K(\vec{r}, f)$ is the local noise source term. We show in this paper that this is but an approximation, valid only for studying the noise of long devices. Indeed, the noise sources are correlated over short distances, and this should be taken into account when modeling the noise of submicron devices. We could derive the formal expression of $S_{\Delta j}(\vec{r}, \vec{r}', f)$ at thermal equilibrium for the diffusion noise in a non polar semiconductor with acoustical, optical and intervally phonon scattering (typically silicon). Let $\Delta j_\alpha(\vec{r}, t)$ the fluctuating part of the current density at point $\vec{r}$ along the direction α. The correlation function of Δj_α

$$C_{\Delta j_\alpha}(\vec{\rho}, \theta) = \overline{\Delta j_\alpha(\vec{r}, t)\, \Delta j^*_\alpha(\vec{r} + \vec{\rho}, t + \theta)}^{\,t}$$

is given by :

$$C_{\Delta j_\alpha}(\vec{\rho}, \theta) = q^2 n(r) \int f_o(\vec{k})\, v_\alpha^2\, e^{-\frac{|\theta|}{\tau(\vec{k})}} \delta(\vec{\rho} - \vec{v}\,\theta)\, d^3k \qquad (1)$$

where $\vec{v} = \frac{1}{\hbar}\vec{\nabla}_k \mathcal{E}(\vec{k})$, $v_\alpha = \frac{1}{\hbar}\partial\epsilon(\vec{k})/\partial k_\alpha$, $\tau^{-1}(\vec{k}) = \int P(\vec{k}, \vec{k}')d^3k'$, $P(\vec{k}, \vec{k}')$ is the transition rate between states $\vec{k}$ and $\vec{k}'$, $f_o(\vec{k})$ is the thermal equilibrium distribution function. Eq.(1) shows that $C_{\Delta j_\alpha}(\vec{\rho}, \theta)$ can be considered as a superposition of Dirac functions at points $\vec{\rho} = \frac{\theta}{\hbar}\vec{\nabla}_k \mathcal{E}(\vec{k})$, weighted by $f_o(\vec{k})\exp[-|\theta|/\tau(k)]$, thus giving a shape as indicated figure 1.

$$S_{\Delta j_\alpha}(\vec{r}, \vec{r}', f) = 4\int_0^\infty \cos 2\pi f\theta \,.\, C_{\Delta j_\alpha}(\vec{\rho}, \theta)\, d\theta$$

has the same shape as $C_{\Delta j_\alpha}(\vec{\rho}, \theta)$. Obviously $S_{\Delta j_\alpha}(\vec{r}, \vec{r}', \theta)$ is not a

Dirac function of $\vec{\rho} = \vec{r} - \vec{r}'$. Numerical results will be presented for p-type silicon.

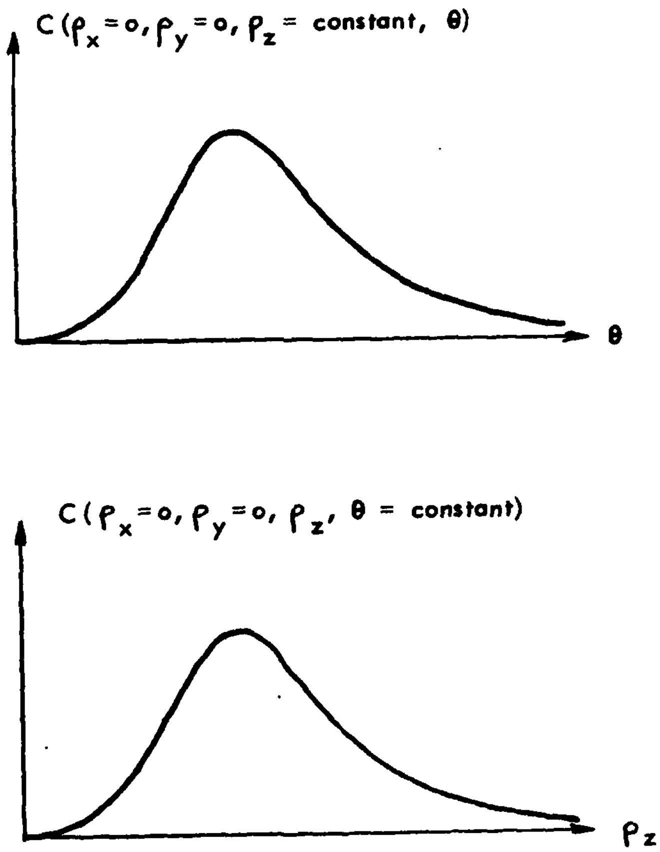

Fig. 1

Variations of $C(\vec{\rho}, \theta)$ versus θ and versus ρ_z.

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SIMULATION OF DIFFUSION NOISE IN A DEVICE

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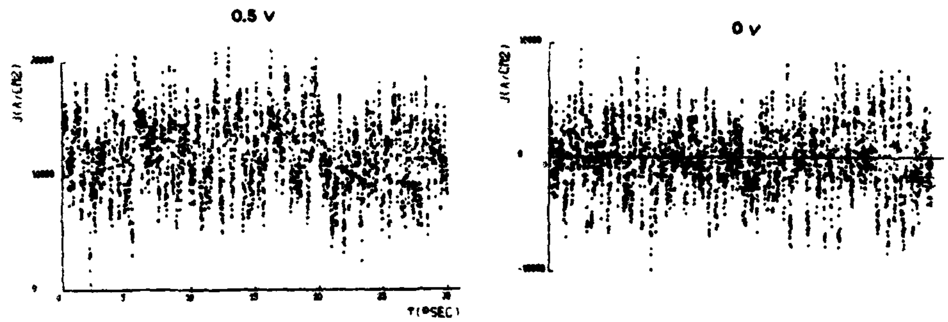
The advantage of Monte Carlo simulation technique is twofold : it is based on microscopic models of carrier dynamics thus yielding fluctuations in a system and it gives macroscopic information with suitable averages of the various estimators. By studying the self-consistent behaviour of the electrons in the structure, we obtain the I(V) characteristic of the device, as usual, but we can also easily get the current fluctuations and study the diffusion noise as well.

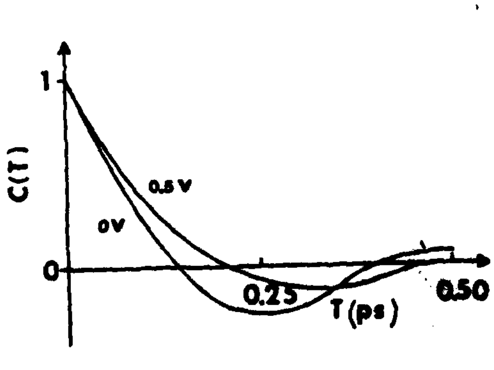
The individual motion of each simulated electron depends at any time on the local electric field and on the various possible interactions the carriers may undergo with the lattice and the impurities. Thirteen interactions such as intervalley, polar and non polar optical and acoustic phonons are considered in accordance with the energy and the wave vector of the particle. The local electric field is calculated at each time step by solving Poisson's equation as we known the instantaneous distribution of the electrons in the device. So making use of the individual velocities of the electrons we can deduce the instantaneous current in the structure for each integration time step (i.e. every hundredth of a picosecond). We may have access to the current noise spectral density by Fourier transforming the current-current correlation function in a suitable time window.

With this method, our purpose is to study the influence of the operating temperature on the diffusion noise in a onedimensionnal N I N GaAs device for various applied bias voltages, and to study the noise in an heterojunction GaAlAs-GaAs device as well.

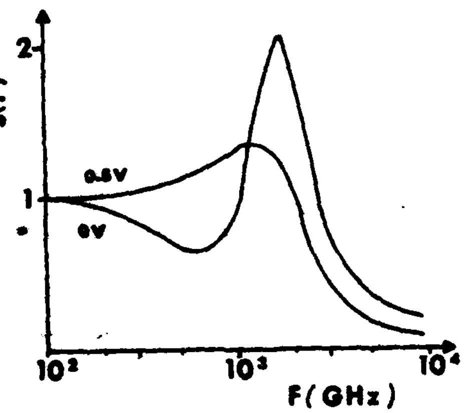
As an example, we present here a study of the N I N - GaAs structure at room temperature. We draw attention on the fact that the numeric values obtained here fit those calculated using Nyquist's theorem.



Current fluctuations in N I N GaAs at room temperature for applied voltages of 0 volts and 0,5 volts.



Correlation function of current noise



Noise spectral density

MONTE-CARLO PARTICLE MODELLING OF NOISE IN SEMI-CONDUCTORS

C Moglestue

GEC Research Laboratories

Hirst Research Centre

Wembley UK.

The two important mechanisms of transport in semi-conductors is the free flight of the carriers in the local field and their interaction with the host lattice. Because of fluctuations in the local fields, particle velocities and frequency of the various scattering events, noise will result. The Monte-Carlo particle model simulates transport by following the transport histories of individual particles. Noise will therefore result in this model. Superimposed on this there will be model noise caused by the computational aspects such as limitation in the number of particles followed and the finite resolution of the solution of the Poisson equation. A correction for model noise may not be straightforward.

To make modelling feasible we make the same assumptions as were used in Boltzmann transport theory: (i) scattering events take place instantaneously, and (ii) the particles can be regarded as classical and noninteracting during free flight.

The correlation in the current for <u>one</u> particle of times t and t + T is, apart from constant factors $\langle \Delta k(t).\Delta k(t+T)$ where Δk represents the deviation from the mean wave vector, and $\langle A \rangle$ denotes a summation over all possible states, weighed against the probability of being realised. The correlation current for N particles is proportional to $N\langle \Delta k(t).\Delta k(t+T)\rangle$.

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To solve Poisson's equation the region in which the particles move is divided into a uniform rectangular tubular mesh with $N_x N_y$ cells in the x and y-direction of size h_x and h_y, respectively, and extend over the entire length L in the z-direction. The local field is defined by the externally applied bias, the background doping charge and the charge of the mobile carriers. Because of the latter the local fields will fluctuate. Poisson's equation, therefore, has to be solved at regular intervals δT. We can only follow the individuals of a subpopulation of $N_s = \nu N_x N_y$ particles. Here ν represents the average number of such particles per cell required for charge neutrality. These particles represent a charge $e_s = n\, h_x h_y e/\nu$ (n is the density of real particles and e their charge for the purpose of solving Poisson's equation and estimating the current. Their correlation current contains N_s instead of N, the noise current will thus be exaggerated by $\sqrt{L h_x h_y n/\nu}$.

Additional terms to the simulated noise current come from the mesh and time intervals used when solving Poisson's equation, giving an additional term $C h_x h_y N_x B/\nu$ where C is a function of δT, and B is a factor reflecting the actual shape of the domain simulated.

The temporal Fourier transform of our correlation current is near constant for low frequencies, decreases like 1/f for frequencies corresponding to that of scattering.

By simulating the current through a rectangular block of GaAs, we have verified our predicted dependency of the noise on the various model parameters $h_x h_y N_x$ ν and δT.

L1

MASTER EQUATION FOR QUANTUM BROWNIAN MOVEMENT

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Peter Talkner, Institut für Theoretische Physik,
Universität Basel, Klingelbergstrasse 82, Ch-4056 Basel

The problem to describe damping of a quantum system arises in fields as diverse as quantum optics, nuclear physics, and low temperature physics. In classical systems effects of dissipation are frequently described in terms of Langevin equations or stochastically equivalent Fokker-Planck equations. These semi-phenomenological Fokker-Planck models are very useful since one avoids to study the dynamics of the "environment" in detail. If both thermal and quantal fluctuations are of importance, the Fokker-Planck equation has to be replaced by a quantum master equation.

Master equations have been used successfully, e.g., in quantum optics and spin relaxation theory. However, this conventional theory of quantum Markov processes is based on the weak coupling master equation which holds only if $\gamma \ll \omega_0$ and $\hbar\gamma \ll k_B T$, where γ is a characteristic damping constant, ω_0 a natural oscillation frequency, and T the temperature. Hence, the approach fails for strongly damped systems, slowly moving systems, and systems at low temperature.

Based on statistical mechanical considerations we have obtained a new master equation describing the irreversible process of damped quantum systems. Our approach is not

subject to the above restrictions and it can be used to study phenomena as, e.g., low temperature Johnson noise, the inversion resonance of molecules, or the tunnelling of a trapped flux in a SQUID. For a Brownian particle moving in a potential $V(q)$ the master equation reads

$$\dot{\rho}(t) = -\frac{i}{\hbar}\left[H,\rho(t)\right] - k_B T\gamma m\hbar^{-2}\left[q,K\left[q,K^{-1}\rho(t)\right]\right]$$

where $H = p^2/2m + V(q)$ is the Hamiltonian and

$$K\rho = (\beta \operatorname{tr} e^{-\beta H})^{-1} \int_0^\beta d\alpha\, e^{-\alpha H}\, \rho\, e^{-(\beta-\alpha)H}$$

is the Kubo transformation. The master equation is shown to obey the symmetry of detailed balance leading to a quantum analogue of the reciprocity relations, and the fluctuation-dissipation theorem is obtained. The dynamics of the mean values is in accordance with Ehrenfest's theorem, and the usual Fokker-Planck equation is recovered in the classical limit.

The approach is used to study the tunnel effect of a bistable system at low temperatures.

TUESDAY MORNING

ROOM B

L1

1/f NOISE IN BIPOLAR TRANSISTORS

1/f Noise in Modulation-doped Field Effect Transistors

by Kuang-Hann Duh, A. van der Ziel*

We report here low frequency noise measurements in "normally on" modulation-doped GaAs transistors(MODFETs)[1-3]. The devices had a 1 μm gate and a 4 μmeter distance between source and drain.

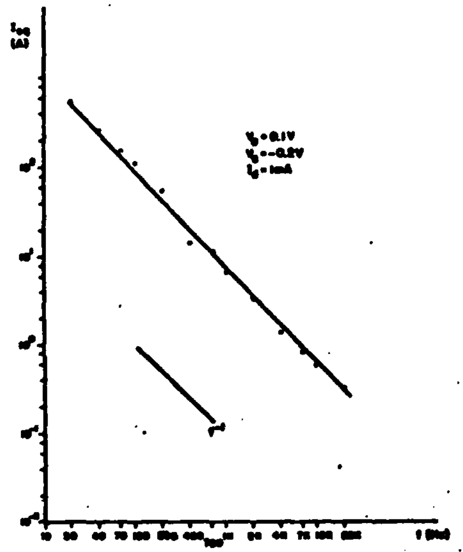

Fig. 1. Ieg versus frequency for MODFET device at $V_d = 0.1$ V, $V_g = -0.2$V, $I_d = 1$ mA

Figure 1 shows the equivalent saturated diode current Ieg, versus frequency for $V_d = 0.1$ V, $V_g = -0.2$ V. The background equivalent saturated diode current of the circuit was estimated to be 5.4×10^{-4} amps so that the device noise is orders of magnitude larger than the background noise. We evaluated Hooge's parameter α and found a value of about 3×10^{-4}, comparable to relatively noisy MOSFETs.

Figure 2 shows Ieg versus the drain voltage V_d at a frequency of 400 Hz. The noise varies as V_d^2 at low V_d and saturates when V_d saturates; this agrees also with what is found for MOSFET.

As said before, the 1/f noise resembles that of a MOSFET. The top n^+AlGaAs layer under the gate is depleted of electrons, the electrons are in the GaAs channel, where they can interact with traps in the AlGaAs layer near the interface by tunneling. The 1/f noise should therefore be of the number fluctuation type. The results of Figure 2 fit very well with this picture.

We calculated the trap density (N_T)eff from our data and found a value of about $10^{14}/cm^3$, assuming a tunneling parameter ε of 10^7 cm^{-1}. Since the magnitude of the noise is proportional to (N_T)eff/ε, $10^{14}/cm^3$ is comparable to p-channel MOSFETs (n-channel MOSFETs usually have the value about $10^{15}/cm^3$).

When one extrapolates the noise data at saturation to high frequencies, one comes to the conclusion that the device should show thermal noise in the 10-30 MHz frequency range. We are looking into that possibility and hope to give a report on the thermal noise of these devices at a later data.

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*The research at Dept. of Electrical Engineering of the University of Minnesota was funded by NSF.

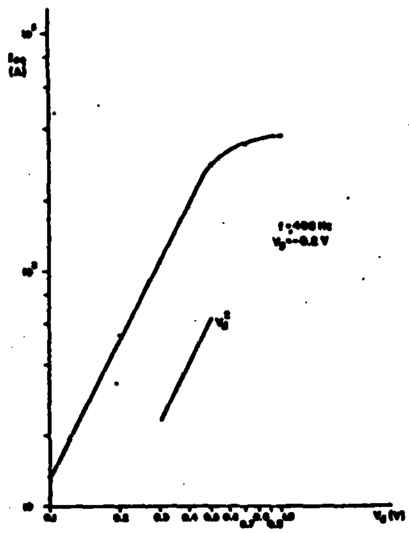

Fig. 2. I_{eq} versus V_D for MODFET device at f = 400 Hz, V_g = -0.2 V.

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L1

ATOMIC IMPURITIES RELATED LOW-FREQUENCY NOISE IN BIPOLAR TRANSISTORS

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Acting as deep levels or, in some cases, introducing surface states/1/ the transition metallic impurities(Au, Cu, Fe, etc) are capable to generate both 1/f(2) and g - r noise/3/ in silicon. How these impurities affect the low - frequency noise of a bipolar transistor structure is shown in Fig.1, where the noise spectra of three ungettered(a,b,c) and one gettered(d) devices are comparatively figured. Impurities such as Au and Cu were observed through DLTS analysis in ungettered devices, while no traces of impurities appeared in the gettered device. The noise level of the ungettered devices depends on whether dislocations are or not present in the emitter-base junction. Therefore, the effect of metallic impurities on the low - frequency noise can be accurately evaluated in the absence of crystallographic defects only.

Studying the effect of Si_3N_4 - preoxidation gettering on the bipolar transistor's noise, it has been found that the noise's evolution closely follows the introduction of lattice defects in the emitter's area(Fig. 2). At an optimum annealing time(3hrs), impurities with atomic radius close to the silicon one(1.173Å) were observed in control wafers using proton - induced X - ray analysis(Fig.3). Impurities with greater atomic radius were observed for times lower/greater than the optimum time. Different misfit stresses induced by atomic impurities can account for the generation of the lattice defects. It is thus obviously that besides the before - mentioned mechanisms, the atomic impurities act as nuclei for the process-induced defects which are in their turn another source of fluctuations.

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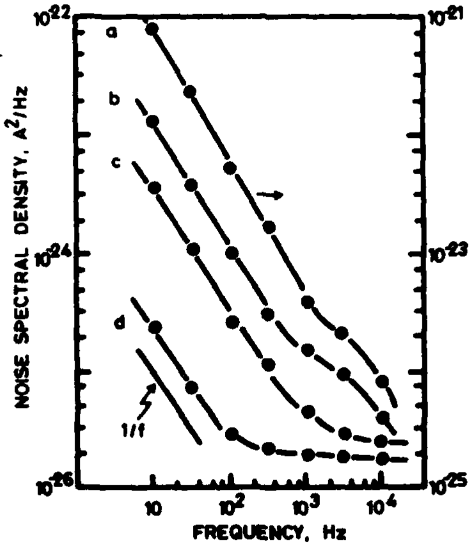

Fig. 1

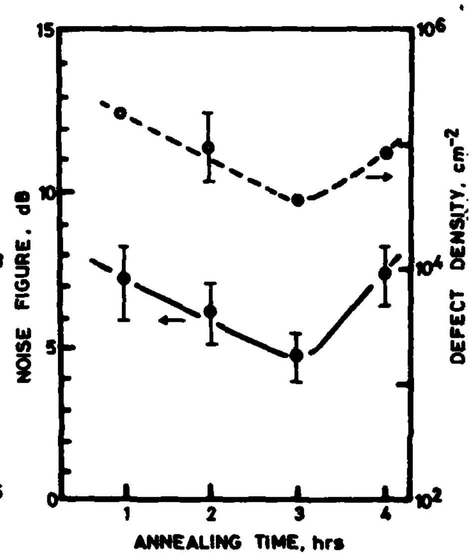

Fig. 2

Fig.1 - The noise spectra of : ungettered transistors (a- 10 dislocations, b- 2dislocations, c-zero dislocations) and gettered transistor (d-zero disloc). The defects were delineated using Sirtl etching.

Fig.2 - The dependence of low-frequency noise figure (measured at 10Hz, I_C=10µA) and defect density on the annealing time.

Fig.3 - The results obtained by proton-induced X-ray analysis of the control wafers.

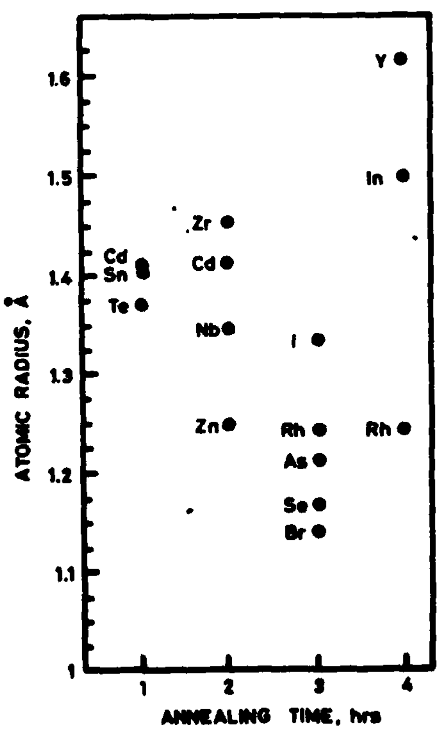

Fig. 3

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1/f NOISE IN BIPOLAR TRANSISTORS

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Department of Physics, University of Lancaster, Lancaster, UK

Noise and static characteristic measurements have been performed on a large number of BC413, low noise silicon NPN bipolar transistors. The results are presented in two parts: a statistical analysis describing the correlation between different pairs of experimental variables and a detailed analysis of a few transistors which includes the temperature dependence between 77 K and 335 K. An example of the statistical analysis is shown in fig.1. The correlation shown is between the excess current noise measured at 1 Hz and the reverse biased emitter base junction leakage current, I_{EBO}, measured at 1 V.

The measurements on the individual devices indicate that for these transistors there is little excess voltage noise and the excess current noise can be represented by a current source at the base-emitter junction. The intensity of this source is proportional to $I_B'^2$ where I_B' is the non-ideal base current in these devices[1]. The location of the noise is found to be not in the base resistance[1] or the surface recombination velocity[2]. Possible mechanisms for the noise are discussed with the evidence relating to each.

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Work supported in part by Ferranti Semiconductors and SERC.

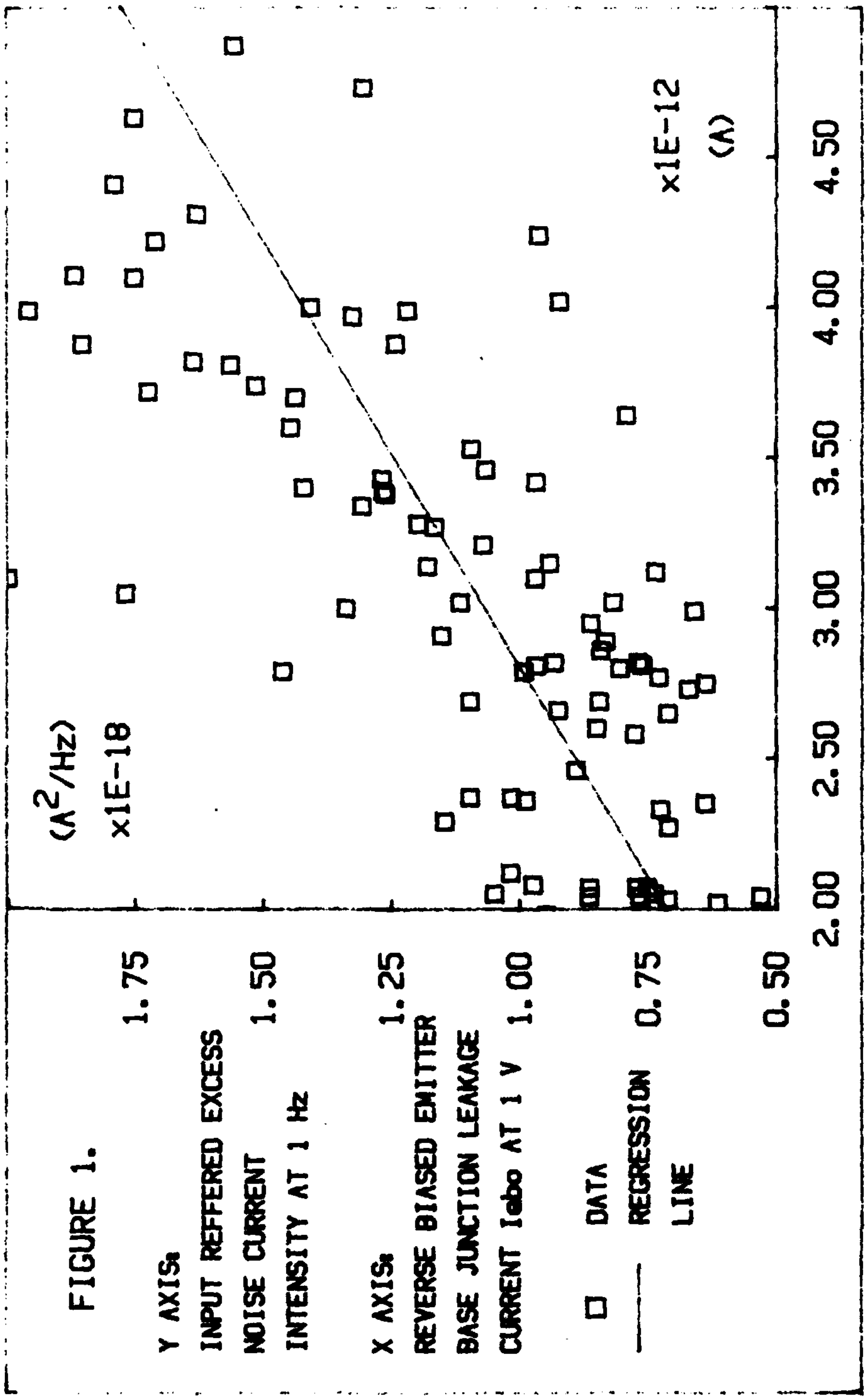
FIGURE 1.
Y AXIS:
INPUT REFFERED EXCESS
NOISE CURRENT
INTENSITY AT 1 Hz
X AXIS:
REVERSE BIASED EMITTER
BASE JUNCTION LEAKAGE
CURRENT Iebo AT 1 V
DATA
REGRESSION
LINE
(A2/Hz)
x1E-18
1.75
1.50
1.25
1.00
0.75
0.50
2.00
2.50
3.00
3.50
4.00
4.50
x1E-12
(A)

<u>Mobility-fluctuation 1/f noise identified in silicon $P^{+}NP$ transistors.</u>

J. Kilmer, A. van der Ziel, and G. Bosman, Department of Electrical Engineering, University of Florida, Gainesville.

The magnitude and location of mobility-fluctuation 1/f noise sources have been identified by means of biasing a PNP transistor in a common emitter configuration with first a high and then a low source resistance[1]. A computation of the noise from the standard equivalent circuit shows that a low source resistor in the base lead isolates the collector noise sources, whereas a high source resistor isolates the base noise sources. The results are shown in Fig. 1, where S_{LR_s} refers to the noise observed with a low source resistance and S_{HR_s} to the noise observed with a high source resistance; all noise is referred to

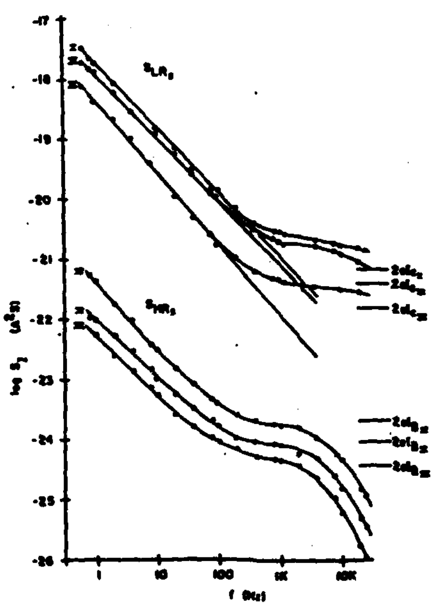

Figure 1

the input. One easily shows that $S_{LR_s} \approx S_{I_{Ep}}$ while $S_{HR_s} \approx S_{I_{En}}$; here I_{Ep} is the emitter to collector hole diffusion current, while I_{En} is the current due to electrons, injected from the base into the highly degenerate emitter region.

According to Kleinpenning[2)] and to van der Ziel[3)], $S_{I_{Ep}}$ is due to diffusion-fluctuation 1/f noise (linked to mobility-fluctuation 1/f noise by $S_{D_p}/\overline{D}_p^2 = S_{\mu_p}/\overline{\mu}_p^2$). From Kleinpenning's expression we computed $\alpha_H \geq 2\times10^{-6}$. Values of this magnitude are of the order of magnitude measured for room temperature according to Bosman et al[4)]. Interpreting in a similar way the base-current noise, we find for the highly degenerate emitter a Hooge parameter $\alpha_H \geq 5\times10^{-8}$; this lower value is due to an impurity-mobility reduction factor of about 100. We finally note that there is no indication of an emitter-base noise source due to oxide surface traps, as occurring in transistors of a former period[5)].

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L1

F^{-1} CURRENT NOISE IN THE BULK OF SHORT DIODES AND BIPOLAR TRANSISTORS

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** C.I.T. ALCATEL, Centre de Villarceaux, 91000 LA VILLE DES BOIS (F)

The existence of distributed 1/f current noise within the intrinsic regions of the emitter and (or) the base of integrated bipolar transistors is demonstrated from a careful analysis of noise factor measurements.

At low level (when crowding and high injection phenomena are negligible) this noise is approximately proportional to the collector current and is independent from the emitter area as shown in figures 1 and 2.

By analogy with models attributing 1/f surface noise to carriers trapping by interface states we assume that the 1/f bulk noise results from a similar mechanism occuring in semiconductor deep traps.

In short diodes we show that the spectral density of minority carriers follows an 1/f law in an extended frequency range consistent with experimental data.

Using this mechanism as a starting point, we propose a current fluctuation model and we derive the explicit relationship of the spectral density of the current noise as a function of trap characteristics, geometrical parameters and biasing conditions.

This relationship accounts for observations carried out in bipolar transistors. In addition it shows that 1/f noise may be generated within quasi neutral regions of either the emitter or the base.

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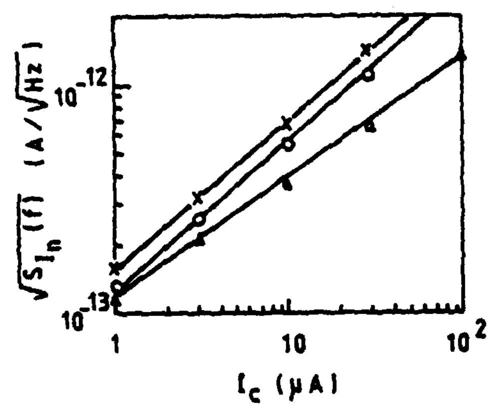

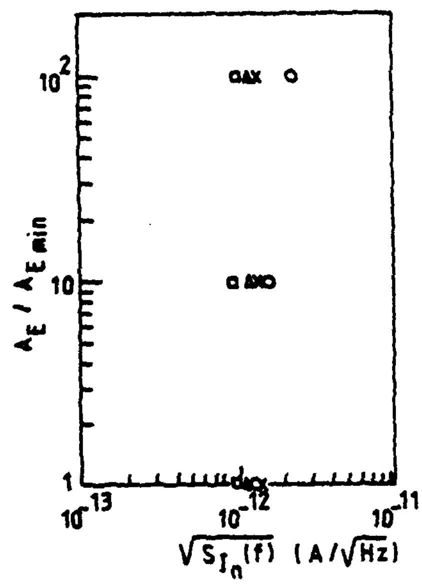

FIGURE 1 - Input current noise VS collector current in integrated PNP bipolar transistors.
Experimental conditions :
$T = 20°C$, $V_{CE} = 4$ V, $f = 10$ Hz

FIGURE 2 - Input current noise VS emitter area.
Experimental conditions :
$T = 20°C$, $V_{CE} = 4$ V, $f = 10$ Hz
$I_c = 10$ μA

L1

Low Frequency Noise Due to Emitter-Edge Dislocations in npn Transistors

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The effect of emitter-edge dislocations on the low-frequency noise of bipolar transistors was studied via phosphorus surface concentration. Five npn bipolar transistor batches with phosphorus surface concentration ranging from (3.5 - 10) x $10^{20}cm^{-3}$ were manufactured on n-type, 4-6 ohm-cm, (111) Czochralski silicon wafers. In order to reduce the effect of metallic contaminants, all the wafers had undergone a preoxidation gettering with Si_3N_4 on the back-side, in N_2 + 1% O_2, at 1100°C, for 3 hrs. Different phosphorus surface concentrations have been realized using different in situ oxidation times (prior to phosphorus deposition) and a single phosphorus bubble rate. The phosphorus surface concentration was determined by V/I and junction depth measurements. The defects were delineated using Sirtl etch and observed by interference contrast microscopy and SEM.

The noise factor was measured at a collector current of 10 μA and at a frequency of 10 Hz. Its dependence on the phosphorus surface concentration is shown in Fig. 1*. A sudden and appreciable increase in the noise level is observed for concentrations greater than 4.3 x $10^{20}cm^{-3}$. This limit of concentration is usually considered to be the limit above which misfit dislocations are generated[1]. Although the selective etching is not proper for misfit dislocation revealing, some areas of misfit dislocation networks were observed inside the emitter surface. It appeared from our observations that these dislocations did not traverse the emitter-base junctions. Emitter-edge dislocations have been generated by the phosphorus diffusion and they were, by far, the dominant defect observed on the control wafers. Their total density was evaluated in an area around the emitter at a distance of 10 μm from the emitter edge, and the results are presented in Fig. 2. Like noise, the defect density follows the same evolution. Moreover, an abrupt change in defect density from about 5 x 10^4cm^{-2} to 10^6cm^{-2} is observed for concentrations greater than 4.3 x $10^{20}cm^{-3}$. From Figs. 1 and 2 we can conclude that the dislocations affect the noise considerably only when their density is in excess of 10^6cm^{-2}. It should be noted here that in MOS devices the fixed interface charge is a function of dislocation density when the density of dislocations is greater than 10^6cm^{-2}[2].

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* It is noted that in Figs. 1 and 2 each point represents the average of the measurements on one hundred transistors.

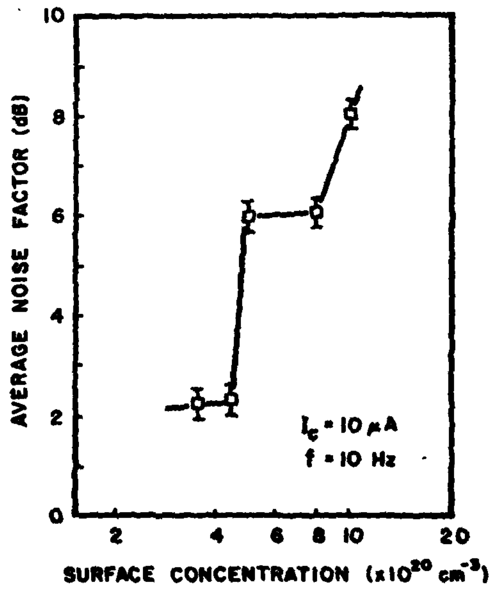

Fig. 1. Dependence of the average noise factor on the phosphorus surface concentration.

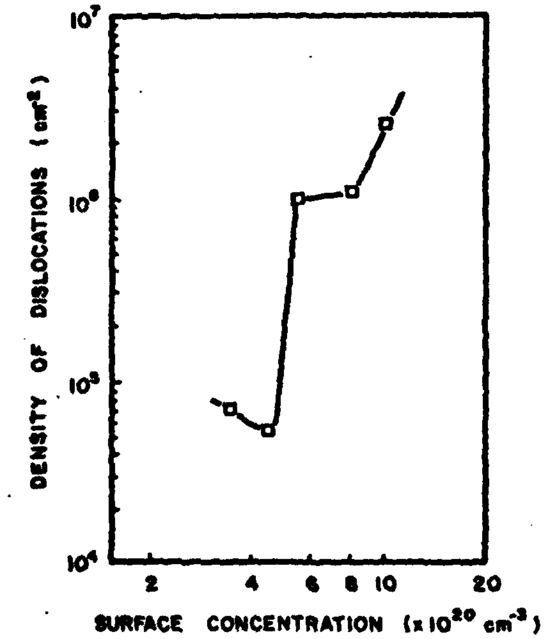

Fig. 2. Dependence of the density (per unit area) of dislocations on the phosphorus surface concentration.

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L1

TUESDAY AFTERNOON

ROOM A

L1

Invited Paper

WHY IS NATURE FRACTAL, AND WHEN SHOULD NOISES BE SCALING?

Benoit B. Mandelbrot and Richard F. Voss*

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ABSTRACT: This talk proposes to restate certain themes from a book by Benoit B. Mandelbrot (The Fractal Geometry of Nature, W. H. Freeman, 1982), and to discuss the possible relevance and usefulness of these themes to the study of scaling or "1/f" noises.

As a preliminary, Mandelbrot's contention that the geometry of Nature is largely fractal will be conveyed with the help of illustrations of totally artificial mountains and clouds generated by Voss. Given the remarkable resemblance of these and more recent scaling "fractal forgeries" to the natural world, the first broad question to be considered is, why should one have expected Nature to be fractal? The three main arguments in The Fractal Geometry of Nature are: A) Many analytical aspects of nature are now known to be scaling: therefore, the corresponding geometric aspects should also be scaling. Straight lines and planes are scaling, but they are rarely found in nature. Fractal geometry offers nature a far richer pallet. B) The prevalence of fractals can be accounted for directly, by real space arguments. Many basic equations of physics are scale-free: for example, the Euler equations of the flow of a nonviscous fluid. The behavior of the solutions is bound to be dominated by the solutions'

singularities. These singularities in turn reflect the symmetry of the original equations and should be expected to be scaling geometric shapes. It is natural to associate turbulence with nonstraight singularities, and hence to trace it back to fractal singularities of fluid motion. This thesis has recently been strongly buttressed by extensive computer simulations. C) The prevalence of fractals can also be accounted for indirectly in a phase space. When a system's time evolution has an attractor, the attractor is in most cases "strange"; which means that it is a fractal. This fact was first established by H. Poincare, P. Fatou and G. Julia, for self-mappings of the complex plane and will be illustrated by exhibiting some fractals associated with the mapping $z \to z^2 - m$.

Against the background of the fractal geometry of nature, the second broad question to be considered is that of the connections between fractals and random time series or noises with a spectral density of the form $1/f^B$. The mathematical similarity is clear: whenever a spectrum can be attached to a fractal (e.g. when the fractal is a vertical section through a relief or a distribution of galaxies), this spectrum is of the form $1/f^B$ and the exponent B is a linear function of the fractal's fractal dimension. Therefore, the remaining issue is that of a possible physical connection. A totally linear system would preserve a scaling, i.e. fractal, geometry, but it could not generate it. However, recent work on turbulence and strange attractor theory demonstrates that nonlinearity, even in seemingly small amounts, can generate fractal structures.

* will present paper

L1

Invited Paper

TRANSITION PHENOMENA INDUCED BY MULTIPLICATIVE NOISE

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THEORY

L 1

On the Distribution of the Level-Crossing Time-Intervals of Random Processes

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Up to now the probability densities $P_0(\tau)$ and $P_1(\tau)$ of a random process for the first downward crossing, resp. upward crossing, of a certain level I within the infinitesimal time-interval $(t+\tau, t+\tau+d\tau)$ given an upward crossing of the level I in $(t,t+dt)$ have not been found. Some approximative solutions have been derived from integral equations or by an excursion model in implicit form. In this paper a novel approach is presented which yields explicit approximative solutions.

The treatment is based on the so-called 4-states model as outlined at 1982 IEEE ISIT Les Arcs (France) by the authors. The four signal states Z_i, $i=1,\dots,4$, characterized by their conditional probabilities S_i, resp. are defined as follows:

Z_1: The process remains above the level I given an upward crossing in $(t,t+dt)$ at least until the time $t+\tau$.

Z_2: The process is found below the level I at the time $t+\tau$ given an upward crossing of I in $(t,t+dt)$ and just one subsequent downward crossing.

Z_3: The process is found above the level I at time $t+\tau$ given an upward crossing of I in $(t,t+dt)$ and at least one subsequent upward crossing during the time-interval τ.

Z_4: The process is found below the level I at time $t+\tau$ given an upward crossing of I in $(t,t+dt)$ and at least two subsequent downward crossings during the time-interval τ.

The 4-states model is modified to a 6-states model by splitting the states Z_3 and Z_4 into two states each, denoted as $Z_3=Z_{31}+Z_{32}$ and $Z_4=Z_{41}+Z_{42}$, resp. The two additional states Z_{32} and Z_{42} with probabilities S_{32} and S_{42}, resp. introduce some relaxation times T_1 and T_2, resp.

Using the well-known Rice's functions $Q(\tau)$ and $W(\tau)$ and assuming

$$P_0 = gS_1 \equiv \frac{Q}{P_+ - S_{32}} S_1 \quad , \qquad P_1 = hS_2 \equiv \frac{W}{1-P_+-S_{42}} S_2$$

one finds the differential equations

$$\dot{S}_1 = -gS_1 \quad \text{and} \quad \dot{S}_2 = gS_1 - hS_2.$$

P_+ is given by the third order density of the process. Setting

$$S_{32} = \int_{\tau-T_1}^{\tau} W(t)dt \qquad \text{and} \qquad S_{42} = \int_{\tau-T_2}^{\tau} [Q(t)-P_o(t)]dt$$

one obtains the explicit approximative solutions

$$P_o^{(6)}(\tau,T_1) = g(\tau,T_1)\ \exp\{-\ G(\tau,T_1)\}$$

$$P_1^{(6)}(\tau,T_2) = h(\tau,T_2)\exp\{-\ H(\tau,T_2)\}\int_0^{\tau} g(t,T_1)\exp\{-\ G(t,T_1)+H(t,T_2)\}dt$$

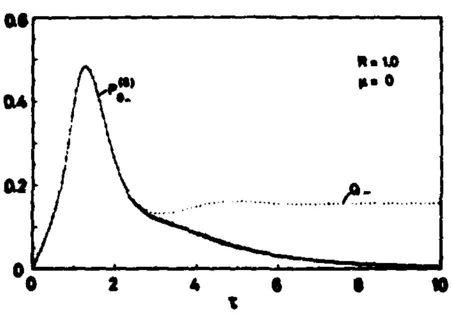
with

$$G(\tau,T_1) = \int_0^{\tau} g(t,T_1)dt \qquad \text{and} \qquad H(\tau,T_2) = \int_0^{\tau} h(t,T_2)dt\ .$$

T_1 and T_2 are evaluated from the first moments of time-intervals between one level-crossing and the first or second successive level-crossing, resp.

The theory was applied to Gaussian and Rayleigh random processes with various power spectra and was verified by computer simulations. The experiments show that the new approximations represent the measured values with an excellent accuracy in wide ranges of τ and I. Thus they outperform previous solutions. A typical result of $P_{0-}^{(6)}(\tau)$, i.e. the probability density for one downward crossing in (t,t+dt) and the adjacent upward crossing in ($t+\tau$,$t+\tau+d\tau$), is illustrated by fig. 1 for a Rayleigh process with fourth-order low-pass Butterworth spectrum and for the normalized level R=1 in comparison to Rice's solution $Q_-(\tau)$.

Fig. 1



L1

FLUCTUATIONS IN DISSIPATIVE STEADY-STATES OF THIN METALLIC FILMS

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Sherbrooke, Québec, J1K 2R1
Canada

We present a realistic calculation[1] of the high-frequency current fluctuations induced by a steady electric field applied to a thin metallic film. At low temperature and under appropriate conditions, these additional fluctuations give a simple way to measure an inelastic relaxation time in the film, in a regime where it cannot easily be measured otherwise because the usual transport coefficients and equilibrium fluctuations are mainly determined by elastic scattering. Physically, the additional fluctuations can easily be understood as arising from an effective electronic temperature rise determined by the balance between the Joule heating rate and the energy relaxation rate, the phonons remaining at the bath temperature. The detailed shape of the isotropic part of the electronic distribution function is however not well described by a local temperature.

Our study also elucidates the physical meaning of previous sophisticated calculations of fluctuations in certain dissipative steady-states by reproducing these results in detail with simpler methods. For the problems we have studied, a local equilibrium extension of the Langevin formalism at the hydrodynamic level works to only about 10%

accuracy when the isotropic part of the stationary distribution function differs from a local equilibrium form. A Langevin type formalism however remains valid and there exist formulae for the Langevin force correlation which depend on the detailed shape of the stationary distribution function.

A quantitative experimental verification of our results would be most important from the point of view of nonequilibrium statistical mechanics. And if our prediction is valid, it could be generalized and then profitably used in the following fields of condensed matter physics: a) in nonequilibrium superconductivity, b) in low temperature refrigeration, c) in the problem of localization.

Reference:

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L1

CALCULATION OF VACANCY NOISE IN MONOCRYSTALLINE METALS

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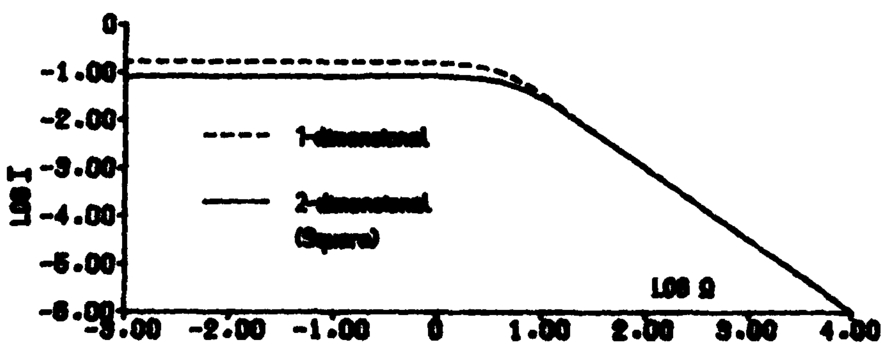
We study nonequilibrium voltage fluctuations in metal films caused by the coupling between the electric current and the vacancy diffusion mode which has a major impact on the excess noise close to the melting point. Our approach is based on a nonlinear Langevin model incorporating the conservation laws and the fluctuation-dissipation theorem.

A phenomenological model describing low frequency excitations in metals can be obtained by following the lines of reasoning traced by Landau and Lifshitz in their theory of fluctuations in fluid dynamics. For cubic crystals in the isothermal and isobaric approximations the charge density ρ and the vacancy density n obey the conservation laws $\dot{\rho} = -\mathrm{div}\,\vec{j}$, $\dot{n} = -\mathrm{div}\,\vec{j}_n$, where $\vec{j} = \sigma\vec{E} + \vec{h}$ is the electric current and $\vec{j}_n = -D_n \mathrm{grad}\, n + \vec{k}$ is the vacancy flux. $\vec{E}$ is the electric field, σ the electric conductivity, and D_n the vacancy diffusion constant. $\vec{h}$ and $\vec{k}$ are Gaussian random forces with vanishing mean, and their correlations are given by $\langle h_i(\vec{x},t)h_j(\vec{y},s)\rangle = 2k_BT\sigma\delta_{ij}\delta(t-s)\delta(\vec{x}-\vec{y})$, $\langle h_i(\vec{x},t)k_j(\vec{y},s)\rangle = 0$, $\langle k_i(\vec{x},t)k_j(\vec{y},s)\rangle = 2\bar{n}D_n\delta_{ij}\delta(t-s)\delta(\vec{x}-\vec{y})$. The modes are coupled since the electric conductivity σ depends on the vacancy concentration n. This nonlinearity is characterized by the parameter $\beta = -(1/\sigma)(\partial\sigma/\partial n)$.

The quantity of interest is now the noise voltage $\delta V(\omega)$

between two metal cross sections of area A. δV is related to the charge fluctuations $\delta\rho$ by virtue of Poisson's equation, the dynamics of the latter being determined by the Langevin model. In the presence of a steady electric current j, the power spectrum consists of the familiar Johnson noise and a frequency dependent excess noise $S_{neq}(\omega) = \pi^2(j^2\beta^2/\sigma^2A^2)\bar{N}\tau\ I(\Omega)$, where $\bar{N}$ is the average number of vacancies, $\tau = (d^2/\pi^2D_n)$ is a characteristic time associated with the thickness d of the plate, and $\Omega=(\pi^2\tau\omega/2)$ is a scaled frequency. $I(\Omega)$ can be determined analytically for boundary conditions appropriate to monocrystalline thin metal plates: $I(\Omega) = \Omega^{-3/2}(\sinh\sqrt{\Omega}-\sin\sqrt{\Omega})/(\cosh\sqrt{\Omega}+\cos\sqrt{\Omega})$. For samples with a rectangular cross section the problem can be reduced to one remaining integration. Its numerical evaluation is depicted below for a quadratic cross section.

In both cases the excess noise spectrum has a characteristic knee, the position of which allows for the determination of the formation and migration enthalpies of the vacancies.



LIFETIME OF A METASTABLE STATE AT WEAK NOISE

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In the study of various equilibrium and nonequilibrium phenomena such as first order phase transitions, chemical reactions, optical bistability and electronic systems, the lifetime of a metastable state plays a decisive role: e.g. it determines nucleation rates, chemical reaction rates, the quality of optical switches and of electronic systems. Often it determines the long time behaviour of the system.

We suppose that the metastable state is an attractor (fixed point, limit cycle, strange attractor) of a deterministic dynamical system $\dot{\underset{\sim}{x}} = \underset{\sim}{K}(\underset{\sim}{x})$ and that the domain Ω of attraction can be left due to a weak perturbation with Gaussian white noise of a strength bounded by ϵ . In order to evaluate the rate of these escapes we surround Ω by an absorbing boundary. Then the mean time $t(\underset{\sim}{x})$ of absorption, determining the lifetime of the state, is the solution of the boundary value problem

$$L^{+}t(\underset{\sim}{x}) = -1 \quad \underset{\sim}{x} \in \Omega , \qquad t(\underset{\sim}{x}) = 0 \text{ for } \underset{\sim}{x} \in \partial\Omega$$

where L^{+} is the backward operator of the Markov process of the perturbed system and where $\underset{\sim}{x}$ is the initial state of the system. For weak noise ($\epsilon \to 0$) we give the asymptotic solution of this equation: Apart from a thin layer near the separatrix $\partial\Omega$ $t(\underset{\sim}{x})$ has the constant value T, and within the layer it decreases to zero like a steep error function. The value of T is given by the ratio of a volume and a surface integral involving an arbitrary solution w of the stationary Fokker Planck equation

$$T = -\frac{\pi}{\epsilon}\,\frac{\int_{\Omega} d^{n}x\, w}{\int_{\partial\Omega} dS_{\alpha}\, w\,(D^{\alpha\beta}\,\partial K^{\gamma}/\partial x^{\delta})^{1/2}}$$

L1

where r is a suitable local coordinate at the boundary pointing into Ω , and where D^{rr} and K^{r} are the diffusion and the drift in r-direction.

In general both w and the separatrix $\partial\Omega$ must be known for the further evaluation of T. Considerable simplifications result if for $\varepsilon \rightarrow 0$ there exists a stationary solution w of the form

$$w = z(x)e^{-\phi(x)/\varepsilon}$$

with z(x) and $\phi(x)$ independent of ε . Then $\phi(x)$ is a Lyapunov function of the unperturbed dynamical system, and both integrals can be evaluated by the method of steepest descent at the respective minima of ϕ . For the volume integral this minimum is the attractor, and for the surface integral it coincides with hyperbolic points of K on $\partial\Omega$. Clearly, the Arrhenius law now follows for T with ϕ (x) playing the role of a nonequilibrium free energy. We note that ϕ (x) may be interpreted as the action function of a Hamiltonian system and that one particular trajectory determines the difference of ϕ involved in T . There are important cases for which this trajectory is easily identifyed, so that a numerical evaluation of both ϕ and z is reduced to solving a set of ordinary differential equations with known initial conditions.

Results which were obtained by different methods are recovered as special cases.

L1

Stabilization by multiplicative noise

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Dynamical systems exhibiting a continuous instability as a function of a certain control or bifurcation parameter have found widespread interest. It is well known that close to the threshold of instability such systems are extremely sensitive to even small perturbations. In many cases, one has only an indirect handle on the control parameter, and it is then subject to inevitable random fluctuations, with experimental control only over its mean value and its variance. The question arises how such random fluctuations of the control parameter influence the behavior of the system near instability. Experimentally, this question has been studied in various systems. The results obtained established the following experimental facts:

(i) The transition, or instability, remained sharp after noise was superimposed on the control parameter.

(ii) The threshold of instability was shifted to larger values of the bifurcation parameter by the application of noise. In other words, the noise acted to stabilize the system for a certain regime of the bifurcation para-

L1

meter.

In this paper we offer an explanation of the mechanism by which the threshold is shifted by noise, but remains sharp. The explanation proposed here turns out to be intimately related to the general question of how a physically given broad-banded multiplicative noise source in a system with widely separated times scales should be represented in stochastic càlculus. In order to obtain explicit results, we study simple models with a long-time scale τ_l, associated with a continuous instability, and a short-time scale $\tau_s << \tau_l$. The correlation time τ_c of the fluctuations of the control parameter satisfies $\tau_c << \tau_l$. For our model we establish that the Gaussian broad-banded noise of the control parameter acts like a Stratonovich noise source on the time scale τ_l, if $\tau_s/\tau_c \to 0$ for fixed spectral noise intensity Q. In the opposite case $\tau_c << \tau_s$, for fixed spectral noise intensity Q, the fluctuations of the control parameter act like an Itô noise source on the time scale τ_l, and the threshold of instability is shifted to larger values. All intermediate cases are also found to occur if τ_c and τ_s are of comparable size. The experimental investigation of these different cases seems therefore feasible and very interesting.

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T U E S D A Y A F T E R N O O N

ROOM B

1/f NOISE IN FET TRANSISTORS

L1

ENERGY LEVELS OF BULK DEFECTS RESPONSIBLE FOR L.F. NOISE IN Si JFETs.

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A previous paper[1] showed that point defects in the bulk, when they are situated in the Debye region at the edge of the channel, are the main sources of low frequency noise in JFETs. Determination of the energy levels of the defects should lead to their identification and help to eliminate these noise sources. Capacitance transient spectroscopy (DLTS) is a powerful method for measuring deep levels in semiconductors. A limitation of the method is that the precision deteriorates at defect concentrations lower than 10^{-4} of the doping level in the material.In any case it is preferable to determine the characteristics of the defects in the device manufactured under normal conditions rather than in specially prepared samples. This paper analyses the noise as a function of temperature,frequency and bias on an individual defect and evaluates the energy level. Data from a large number of such evaluations on various JFETs is presented.

Many n-channel JFETs exhibit noise in the temperature range 77K to 350K and frequency range 10Hz to 10^5Hz which is attributable to 4 classes of defects with energy levels in the range E_c-.15v to midgap. The defect density of each class is estimated to be about $10^{11}/cm^3$ in good JFETs. At least 2 other classes of defect are seen in some devices.

Factors affecting the precision of the calculated energy level will be discussed. It will be shown that activation energies can be determined with greater confidence with 4-terminal JFETs than with 3-terminal JFETs. Precise deteminations are difficult when the effects due to 2 classes of defect overlap. We have been able to find many

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devices in which a defect of one class dominated the spectrum without appreciable interference from another defect.

Emission rates of carriers at defects, in the presence of an electric field, are greater than that due to thermal emission owing to tunnelling. The noise peaks in a JFET occur[1] only when the defect is in a region of the channel where the field varies rapidly although the magnitude of the field is not as large as that in some DLTS measurements.

We have found a significant scatter in the calculated energy levels of defects belonging to one class as evaluated from measurements on different devices even when we only include the favourable situations. The scatter is however no greater than that found in the literature for the acceptor and donor levels of gold which have been extensively documented. We are inclined to the view that these differences are inherent in the behaviour of deep levels as proposed by Lang, et al[2].

The presence of important noise peaks in the temperature range 77K to 100K and their strong dependance on bias conditions will be analysed in the context of published work on generation-recombination noise of donors and hot carrier effects.

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Phys. Rev. B Vol 22, 1980, p 3917

L1

Thermal Noise at Weak Inversion and Limiting 1/f Noise in MOSFETs

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Consider a MOSFET at weak inversion the conductance g(Vo) for unit length according to van Overstaeten et al [1]

$$g(Vo) = \frac{\mu w C_d}{\beta} \exp\left[\frac{\beta}{n^*}(Vg - Vg^*) - \frac{1}{2}\beta\phi_F\right] \exp(-\beta Vo)$$

where $\beta = q/KT$, ϕ_F the Fermi potential difference and

$$Vg^* = V_{FB} + \frac{3}{2}\phi_F + Q_b^*/C_{ox}$$

$$n^* = (C_{ox} + Cd) / C_{ox}$$

Here V_{FB} is the flatband voltage, Q_b^* the depletion change per unit area at the surface potential $\Psi_s = 1.5\,\phi_F$, C_{ox} and C_d are the oxide and the depletion capacitances per unit area, respectively. C_d is a weak function of applied voltage Vo through the surface potential Ψ_s and its value at $\Psi_s = 1.5\,\phi_F$ is denoted by C_d^*; usually one puts $C_d = C_d^*$ throughout. The above expression is correct as long as the effect of the surface state density Nss can be neglected.

Consequently

$$Id = \frac{1}{L}\int_0^{V_d} g(Vo)dV_o = I_{sat}\,[1-\exp(-\beta Vd)]$$

where $I_{sat} = \frac{\mu\omega}{L}\frac{C_d}{\beta} \exp\left[-\frac{\beta}{n^*}(Vg - Vg^*) - \frac{1}{2}\beta\phi_F\right]$

is the saturated current, which is the I_d value for $\beta V_d > 4$. Then

$$g_{max} = \frac{\partial I_{sat}}{\partial V_g} = \frac{\beta I_{sat}}{n^*} = \frac{qI_{sat}}{KT}\left(\frac{C_{ox}}{C_{ox} + C_d}\right)$$

Futhermore

$$S_{I_d}(f) = \frac{4KT}{L^2 I_d}\int_0^{V_d} g^2(Vo)dVo = 2q\,I_{sat}\,[1+\exp(-\beta Vd)]$$

as is found after some manipulations. At saturation the noise thus corresponds to shot noise of I_{sat}, even though the noise is, in fact, thermal noise (Fig. 1). In the Strong Inversion case the difference in noise only a factor 3/2.[2]

The limiting 1/f noise in MOSFETs can be caused by the thermal noise of dielectric losses in the oxide. Let the device have a capacitance Cgs and let the oxide have an effective loss tangent $\tan\delta$, then the equivalent noise resistance due to these dielectric losses will be

$$R_n = \frac{\tan\delta}{\omega C g_s}$$

From Fig. 2, Cgs = 0.47 PF, at f= 100 Hz, Rn = 4MΩ we get $\tan\delta = 10^{-3}$. Rn = $3.7 \times 10^8/f$ ohms.

The best way to observe this hypothetical limiting noise would be to operate the device at saturation at very low inversion. We saw that in that case the noise due to traps on the surface oxide would be negligible. In the 1/f regime of Rn, Rn should be independent of the drain current Id. FIg. 2 shows that this is indeed the case. Because Rn is inversely proportional to Cgs, the limiting 1/f noise is proportional to oxide thickness and inversely proportional to the gate area. We can scale down the oxide thickness to improve the noise performance.

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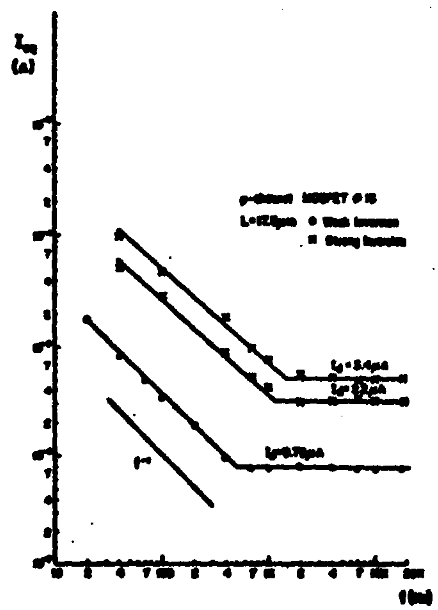

Fig. 1 Low frequency noise spectrum for p-channel MOSFET.

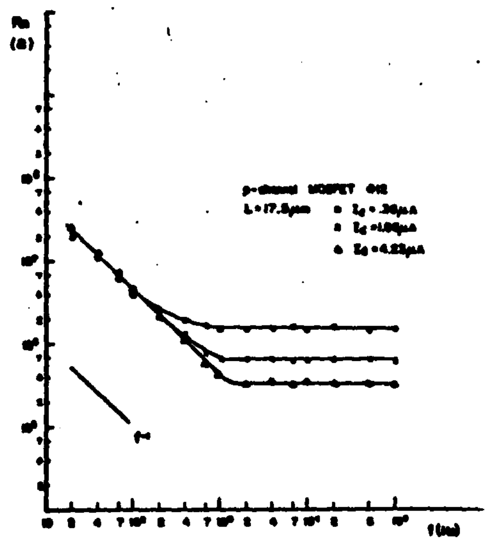

Fig. 2 Noise resistance of p-channel MOSFET at low inversion.

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1/f NOISE IN MOS TRANSISTORS BIASED FROM WEAK TO STRONG INVERSION

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Experimental results on low frequency 1/f noise in MOS transistors (*) are reported, for the whole range of gate bias from weak inversion regime to strong inversion regime. The noise measurement procedure has already been given in a previous paper [1]. Measured values of S_{I_D}/I_D^2 versus V_G at low drain voltage (I_D : drain current ; S_{I_D} : power spectral density of its fluctuations) exhibits a plateau in weak inversion (Fig.1), i.e. for our measurements at V_D = 20 mV drain currents from 1.8 nA to 125 nA, followed by a steep decrease in strong inversion.

Mobility fluctuation model is usually described by the Hooge's empirical relation $S_{I_D}/I_D^2 = S_G/G^2 = S_{V_D}/V_D^2 = \alpha/Nf$ [2], [3]. Under this form, this model seems unable to account for the experimental plateau because N strongly varies with the gate voltage in the whole range of gate bias. A more precise description could probably be done and would lead to an $\alpha(V_G)$.

But when using McWorther's model and taking into account all the capacitive components of the small signal equivalent circuit, for an n-channel MOS transistor, we obtain the following expression, valid for every bias :

$$S_{I_D}/I_D^2 = \frac{K\,N_t}{(C_{ox}+C_D+C_{ss}+|\beta Q_n|)^2}\cdot\frac{1}{f} \quad ;$$

K is independent of the bias, C_{ox}, C_D, C_{ss} and $|\beta Q_n|$ are capacitances per unit area (respectively : oxide capacitance, depletion capacitance, surface state capacitance and capacitance related to the channel charge). For weak inversion $|\beta Q_n| \ll C_{ox} + C_D + C_{ss}$ and $S_{I_D}/I_D^2(V_G)$ is a constant if C_{ss} is low. For strong inversion $|\beta Q_n| \gg C_{ox} + C_D + C_{ss}$ and S_{I_D}/I_D^2 decreases like $1/Q_n^2$. The results of such a theoretical modelisation are given in Fig. 1 and show a good agreement with experimental measurements.

The measured plateau's levels for several low Nss transistors

($N_{SS} < 2 \times 10^{10}$ $eV^{-1}cm^{-2}$) with different oxide thicknesses and bulk dopings also agree with the relation $S_{ID}/I_D^2 \sim (C_{ox} + C_D)^{-2}$.

At low temperature (77 K), the plateau disappears and is replaced by a decreasing noise level, the slope of which depends on the quality of the device. This result can be explain by an increase of C_{SS} when the Fermi level approaches the conduction band [4]. Such a decreasing level must also be observed at 300 K for bad quality devices (high N_{SS}) ; this is the reason why Aoki and al. [5] didn't get any plateau at 300 K on their transistors with $N_{SS} \sim 3$ to 4.5×10^{11} $eV^{-1}cm^{-2}$.

(*) Devices supplied by Thomson CSF (St-Egrève, France) which supported this work.

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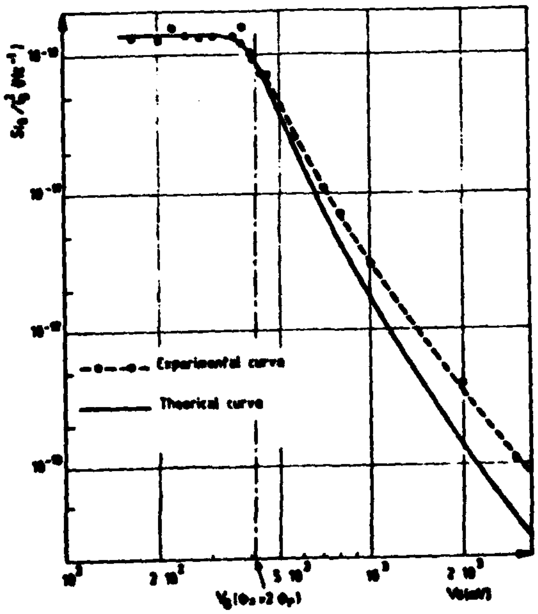
Figure 1 : $S_{ID}/I_D^2(V_G)$ in the whole range from weak to strong inversion regime, at low V_D. T = 300 K, f = 15 Hz, Z/L = 200/15



1/f noise in metal-nitride-oxide-silicon (MNOS) memory transistors

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1/f noise in MOSFET's has been the subject of research for a long time. In spite of the many efforts in explaining the physical phenomena behind this type of noise in MOS transistors, a generally accepted theory is still lacking. In fact two models have been developed which are based on different physical processes: the carrier density fluctuation model based on the Mc Whorter theory of tunnelling and the mobility fluctuation model based on the Hooge empirical α-model. Recently a combination of the two models was proposed for n-channel silicon gate MOS transistors (1).
Whereas 1/f noise behaviour in MOS transistors has received great attention only scarce information is available on the 1/f noise in MNOS memory transistors, although this transistor is a unique tool for checking the validity of the above mentioned models. This paper reports on an extensive study of 1/f noise in p-channel Aluminum gate and n-channel polysilicon gate MNOS transistors. For this purpose both hydrogen annealed MNOS transistors (2) and unannealed devices were used. The interface state density for the former devices is reduced to values close to 1×10^{10} $cm^{-2}eV^{-1}$ whereas for the unannealed devices this value lies around 7×10^{11} $cm^{-2}eV^{-1}$. One of the main reasons why the MNOS device is such an interesting device for the 1/f noise study is that its $Si\text{-}SiO_2$ interface can be degraded by Write/Erase cycling so that its surface state density can be varied in a continuous way from 1×10^{10} to about 3×10^{12} $cm^{-2}eV^{-1}$.
So, in one and the same device the interface state density and the channel mobility can be varied over a wide range, allowing a direct check of the main features of the two 1/f noise models.
The conclusions from the detailed study which will be reported on can be summarized as follows:
1. $1/f^{\gamma}$ ($\gamma \sim 1$) is always observed both in p-channel and n-channel MNOS transistors, even after severe degradation. The effect of

hydrogen anneal is reflected in both a reduction of noise and surface state density.

2. For transistors with the same geometry, p-channel and n-channel devices show the same noise values.

3. The theoretical equation proposed for p-channel MNOS devices (3) also gives excellent agreement for n-channel devices, even after degradation.

4. The 1/f noise increases linearly with the surface state density as expected by theoretical prediction based on the Mc Whorter model (3), see figure 1. The surface state density was obtained with the charge pumping technique (4). The predictions of the mobility fluctuation model are not at all confirmed in our experiments.

5. In both n-channel and p-channel transistors thesame type of degradation effect on noise and surface state density upon cycling is observed. Figure 2 shows the increase of both quantities as a function of the stressing time for p-channel devices.

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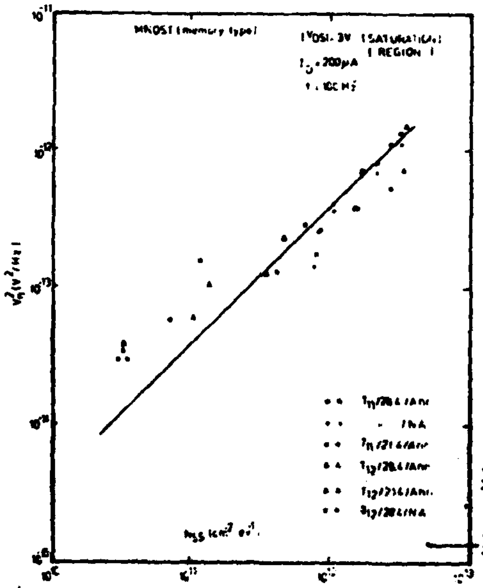

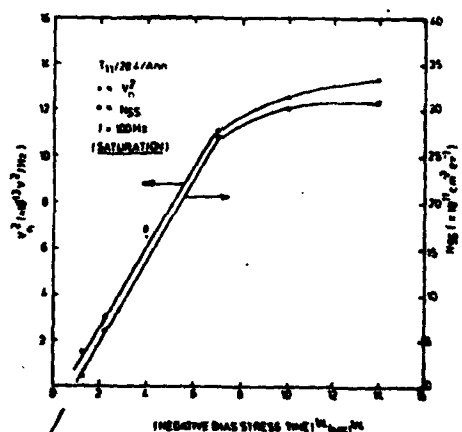

Fig. 2 : Evolution of v_n^2 and N_{SS} with stressing time

Fig. 1 : 1/f noise as a function of N_{SS}

L1

ORIGINS OF F^{-1} NOISE IN MOS TRANSISTORS

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- : -

In MOST F^{-1} noise is often attributed either to fluctuations in the number of free carriers induced by interface states and oxide traps (CLS-FS model) or to mobility fluctuations due to lattice scattering (HV model). In order to validate,these models experimental investigations have been carried out by several authors. In numerous cases, the results obtained were not conclusive and some doubts persist concerning the origins of F^{-1} noise in MOST.

In order to elucidate this question, MOST were irradiated with X rays. In effect, it is well known that low energy X rays increase the oxide traps density and the density of interface states. However, they do not damage the silicon lattice. One can conclude that X rays are ineffective on HV noise and that they must change CLS-FS noise. Then, one can, in principle, establish the difference between these two types of noise.

The transistors used in this study were manufactured in our laboratory. Their characteristics are the following : P type substrate, impurity concentration $N_A = 2 \times 10^{16}$ At/cm^3 ; width $Z = 700$ µm, length $L = 120$ µm ; oxide thickness $X_o = 2000$ A° ; gate metallisation : chromium ; transconductance $g_m \approx 5 \times 10^{-6}$ A/V electron mobility $\mu_n \approx 900$ cm^2/V.S.

The X ray generator was of the A equivolt type from C.G.R. It worked at 150 kV and delivered a dose rate equal to 250 rads/mn. During irradiation, transistors were short-circuited. The major parameters measured in this experiment were : a) the voltage noise at the drain terminal S_{V_D} in the linear region at drain voltage V_D equal to 50 mV, b) the current voltage characteristics : $I_D(V_D)$, $I_D(V_G)$; c) the capacitance versus gate voltage $C(V_G)$ and finally d) the total surface recombination velocity s_0^* [1].

The analysis of experimental results after irradiation at doses ranging from 0 to 40 krads shows two distinct types of behaviour. Under two krads, F^{-1} noise, the slopes of the curves $I_D(V_G)$ and $C(V_G)$ are practically constant within experimental accuracy, while, the turn on voltage V_T decreases, s_0^* increases and the curves $C(V_G)$ moves toward negative gate voltage. Above two krads, F^{-1}, V_T, s_0^* increase, the slope of $I_D(V_G)$ decreases, and a gradual distorsion appears in the $C(V_G)$ curves. In both cases, F^{-1} noise is proportionnal to V_D^2 and $(V_G - V_T)^{-2}$.

These results can be interpreted as follows. At low doses, the principal effect of X rays is to induce a positive oxide charge and

recombination centers at the interface Si - SiO_2. These centers do not modify the slope of the $C(V_G)$ curves because their density is too low. The HV model predicts $S_{V_D}/V_D^2 \propto (V_G - V_T)^{-1}$ while the CLS - FS model gives $S_{V_D}/V_D^2 \propto (V_G - V_T)^{-2}$. Then, the noise seems to be CLS - FS noise. Nevertheless, as noise is constant while s_{δ}^{*} increases there are at least two possibilities : a) the physical mechanism generating noise is of the CLS - FS type and the possible traps induced by low dose X rays do not have the necessary characteristics to give a significant increase in F^{-1} noise, b) the noise is neither of the CLS - FS type nor of the HV type.

At higher doses, X rays induce oxide traps and interface states having a density of the order of the positive oxide charge. The increases in noise could be the result of the CLS-FS mechanism or of mobility fluctuations due to carrier trapping within oxide traps and interface states. These two possibilities will be discussed in details at the conference.

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L1

WEDNESDAY MORNING

ROOM A

Invited Paper

CHAOTIC NOISE IN JOSEPHSON TUNNEL JUNCTIONS

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There has recently been considerable interest in physical systems that are described by non-linear equations and that under appropriate conditions exhibit chaotic behavior. In a chaotic regime, the solutions to the governing equation of motion are aperiodic although, in the absence of external noise in the system, they are completely determined once the initial conditions have been chosen. Systems undergoing chaos may therefore exhibit large levels of noise, and it is important in the design of devices to choose parameters so that chaotic behavior does not occur. We have studied in considerable detail the behavior of Josephson junctions that become chaotic when they are coupled to an appropriate external circuit. We have also simulated their behavior on analog and digital computers.

The experimental configuration consists of a Josephson tunnel junction with critical current I_0 and self-capacitance C shunted with an external resistance R that has a self-inductance L. The behavior of the system is determined by the dimensionless parameters $\beta_C \equiv 2\pi I_0 R^2 C/\Phi_0$, $\beta_L \equiv 2\pi L I_0/\Phi_0$, and $i = I/I_0$; I is the bias current and $\Phi_0 \equiv h/2e$ is the flux quantum. Chaotic effects are found for $i > 1$ when $\beta_C \lesssim 1$ and $1 \lesssim \beta_L \lesssim 25$. The current-voltage (I-V) characteristics of junctions in this range of parameters exhibit numerous regions of stable negative resistance. The voltage noise generated across the junction can be conveniently characterized by a noise temperature $T_N = \langle V_N^2\rangle/4k_B RB$, where $\langle V_N^2\rangle$ is the mean square voltage noise in a bandwidth B.

With the aid of the analog and digital simulations, we can divide the observed noise levels into three general classes. First, there are regions of bias current for which the noise temperature is below the system noise temperature, T_N: Here the junction is in a stable limit cycle (possibly bifurcated). Second, there are a number of relatively broad regions for which the noise temperature is typically of the order of 1,000K. In this region, the junction exhibits chaotic behavior. Third, there are a number of narrow but extremely noisy peaks for which the noise temperature may exceed 10^6K. This noise is generated when the junction switches randomly either between two stable subharmonic modes or between a stable subharmonic mode and a chaotic regime. From simulations of this behavior, we have been able to show that the switching is induced by Nyquist noise in the resistive shunt.

Many of the universal features of chaos are observed in these junctions, for example, period-doubling sequences to chaos, and regions of Pomeau-Manneville intermittency. The Josephson junction has proved to be a useful device in which to study chaotic behavior, since its equation of motion is well known, and accurate comparisons can be made with computer models.

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Invited Paper

Long Time Tail Relaxation Noise

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The purpose of the present paper is to explain the physical mechanism of the noise-induced long-time tail. The critical slowing down or long-time tail in stochastic processes is classified into three categories,[1] namely (i) deterministic, (ii) marginal and (iii) noise-induced long-time tail. The value of the long-time exponent is determined on the basis of the dynamical scaling theory for general nonlinear stochastic processes as well as conditions for the appearance of the noise-induced long-time tail.

(i) The deterministic critical slowing down is caused effectively by the nonlinear deterministic part of the relevant stochastic system.

(ii) The noise-induced long-time tail appears due to the balancing of the noise term and nonlinear term in multiplicative stochastic processes.[2]

(iii) The marginal long-time tail occurs for the marginal case between (i) and (ii).

In particular, we give an exact solution of a multiplicative stochastic process, so-called random growing-rate model described by $dx/dt = (\gamma+\eta(t))x-gx^m$, where $\eta(t)$ denotes the Gaussian white noise. It is rigorously shown that the moment $\langle x^p(t)\rangle$ for possitive p shows a long-time tail of

the form $\langle x^p(t) \rangle \sim t^{-1/2}$ at $\gamma = 0$.

This result can be extended to more general (unsolvable) models, and the universality and scaling of the fluctuation are confirmed.[3]

We also discuss the fractional Brownian motions[4] corresponding to the Levy process or non-markovian noise. In particular we present an interesting physical example of fractional Brownian motions, namely string animals with topological (or geometical) restrictions.[5]

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L1

THEORY 1/f NOISE

FLICKER NOISE IN NON-ELECTRIC SYSTEMS

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The island model yields an unitary theory of the flicker, burst and generation-recombination noises in the electrical systems[1,2], together with the diffusion-noise theory it removes any difference between carrier-number and -mobility fluctuations models[3], and it shows that a pure 1/f noise does not exist physically[4].

In this note we will show that the model may be easily extended to non-electric system (NES) too. This is made possible by the general analysis of the Ref.2 since it takes into account not only the electric drift but also the diffusion of the particles occurring in any entity ensemble in which the quantities retaining unchanged their meaning are the densities n_e and $\underline{J}_e$ of the entities and of their current, respectively, the chemical potential μ, their number N_e and current i_e relative to the islands. They are connected to the corresponding electric ones by the relationships $n_e=n/q$, $\underline{J}_e=-\underline{J}/q$, $\mu=-qu$, $N_e=-Q/q$ and $i_e=-i/q$, where q and Q are the electron and island charge, respectively. In NES, instead, the electric potential v is null everywhere.

By taking into account such relationships in the analysis of Ref.2, one obtains the corresponding equations for NES and in, particular, the relaxation time τ, the current dipole vector $\Delta\underline{\dot{P}}_e$ and the spectrum S_N of the particle-number fluctuations of the island in the form

$$\tau=N_e/i_e,\quad \Delta\dot{P}_e=\underline{J}_e\,\Delta N_e/\bar{n}_e,\quad S_N=4\bar{N}_e\,\tau/(1+\omega^2\tau^2) \qquad , \qquad (1)$$

where $\bar{N}_e=\Sigma N_j\bar{f}_j(1\pm\bar{f}_j)$ is the average entity number of the islands, the - and + signs holding for fermions and bosons, respectively.

According to v=0, $\Delta\underline{\dot{P}}_e$ now can not generate fluctuations Δv between any two probe points N' and M', whereas it can produce fluctuations

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$\Delta I_{eI} = \Delta \dot{\underline{P}}_e \cdot \underline{\nabla} A$ of the *current crossing* a "short-circuit" (SC) connecting N' and M', where $A = \delta I'/\delta I$ is the current gain, $\delta I'$ being the current crossing SC when the current δI is injected in r and it is extracted from M'.

Finally the spectrum

$$S_{I_e} = \int \left[(\tilde{\underline{J}}_e \cdot \underline{\nabla} A)^2 4 \bar{N}_e \ \tau / \bar{n}_e^2 (1 + \tau^2 \ \omega^2) \right] D_I D d^3 x dX_1 dX_2 \quad , \qquad (2)$$

of the total current through SC, being analogous to the one obtained for the electric systems[2], leads to the same subsequent developments and results of their analysis.

The fluctuations in several NES, non-physical too, may be analysed by means of preceding model.

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L1

Theory of 1/f Noise in Metals

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We propose a new microscopic model explaining 1/f noise in metals at relatively high temperature above Debye temperature but below the Fermi energy. The model is based on the scattering of the diffusely propagating conduction electrons due to surface acoustic phonon modes via randomly distributed defects in crystal.

The electron-surface phonon interaction, H_{e-sp}, has non-zero contribution proportional to displacement of the defect atom even when the momentum of the phonon is approached to zero, since the potential due to defects deviates from the one due to the periodically arranged lattice.

From the analytic continuation of the thermal Green's function, we obtain the spectral density of H_{e-sp} as follows

$$S_{H_{e-sp}}(f) = 2N(0)k_B T \coth\frac{\omega}{k_B T} \sum_\lambda \frac{v_s^2}{\rho_0 v_\lambda^2}, \qquad (1)$$

where N(0) is the density of states per spin at the Fermi energy, ρ_0 is the surface mass density, v_s is the strength of the electron-surface phonon interaction and v_λ the velocity of the surface phonon mode, λ. Hence the energy fluctuation of electron has a term proportional to f^{-1} at low frequency.

The spectral density of resistance is approximately given by

$$S_R(f)/R^2 = \left(\frac{\gamma}{C_V}\right)^2 S_{H_{e-sp}}(f), \qquad (2)$$

where R is the resistance of the sample, $\gamma=\frac{1}{R}(\frac{\partial R}{\partial T})$ is the temperature coefficient of the resistance and C_V is the specific heat of conduction electrons. If free electron approximation is used, C_V is given by, $C_V=\frac{2}{3}\pi^2 k_B^2 TN(0)$, for $k_B T<<E_F$. Then eq.(2) is written as

$$S_R(f)/R^2=\frac{9}{2\pi^5}\left(\frac{\gamma}{k_B}\right)^2\frac{1}{N(0)}\sum_\lambda\frac{v_s^2}{\rho_0 v_\lambda^2}\frac{1}{f}\,. \tag{3}$$

The $S_R(f)$ is inversely proportional to the system size, which is consistent with the empirical formula by Hooge.[1] However eq.(3) does not inversely proportional to the total number of mobile charge carrier but to the density of states at the Fermi energy.

There are two types of defects in our model. One is native , for example, impurities. The other is activated by temperature rise, electron bombardment, irradiation of light or any other changes of the external conditions. When an activation type of defect with the activation energy,E_g, is dominant, $S_R(f)/R^2$ is proportional to $e^{-E_g/k_B T}/T^2$ since v_s is proportional to the density of defects and $\gamma\propto 1/T$. Hence we can expect a peak value of 1/f noise as a function of temperature. This is in qualitative agreement with the recent experimental results of Eberhard and Horn.[2]

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L1

Unified Model for 1/f Noise in Semiconductors and Metals

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The defect mechanism suggested for metals[1] has an advantage in obtaining long time constants observed in semiconductors[2] in contrast with the phonon fluctuation hypothesis.[3] Therefore, we propose a model which assumes that the fluctuation of the Fermi energy, which is caused by defect fluctuations, is an origin of the conductivity fluctuation. The 1/f spectrum is attributed to number fluctuations of defects.[1] It is shown that the model leads to results not inconsistent with the Hooge-Vandamme experiment.[3]

Volume effects in semiconductors are studied by assuming trap density fluctuations. For n-type semiconductors with acceptor-type traps the noise current spectral density $S_I(f)$ is found to be

$$S_I(f)/I^2=(\gamma/\Omega nf)(n_t f_t^2/n). \qquad (1)$$

Here, I is the steady current, Ω is the volume of the specimens, n is the density of conduction electrons, n_t is the density of traps, γ is a quantity related to relaxation times of the trap fluctuations, and

$$f_t=[1+\exp(E_t-E_F)/kT]^{-1}$$

where E_F is the Fermi energy and E_t is the energy of trapped electrons. Eq.(1) can be applied to p-type semiconductors too, if n is replaced by the hole density. Eq.(1) indicates that $S_I(f)$ depends strongly on the relative magni-

tude of E_F with E_t.

Surface effects for semiconductors are examined with the use of the depletion layer approximation. At the surface of an n-type semiconductor film the depletion layer is assumed, whose width W is calculated as a function of the surface state density per unit energy D_s. The fluctuation of D_s produces the fluctuation of W, which causes the resistance fluctuation. Consequently, we obtain

$$S_I(f)/I^2=2\gamma\gamma^2(a+b)n_DW^2/abn_sNf, \qquad (2)$$

where γ=dlnW/dlnD_s, N=Ωn, a is the width, b is the thickness of the film, n_D is the donor density, and n_s is the surface state density per unit surface area. It is shown that n_DW^2 is independent of n_D for small n_D, while it is proportional to $1/n_D$ for large n_D. Therefore, $S_I(f)$ given by Eq.(2) exhibits the carrier density dependence similar to that of Eq.(1).

For metals and degenerate semiconductors we find

$$S_I(f)/I^2=(\gamma\xi^2/N)(n_{def}/n), \qquad (3)$$

where n_{def} is the defect density and ξ is a proportionality constant between the number fluctuation of electronic states and the defect number fluctuation.

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DERIVATION OF THE NYQUIST-1/F NOISE THEOREM

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In the derivation of the Nyquist theorem, such as given, e.g., by Callen and Welton[1], the eigenstates ϕ_n used (Eqs. 1,2,4) have well defined energy. However, the eigenstates ϕ_n that describe the final state of physical current carriers must include corrections due to the infrared-divergent coupling of the carriers to photons and other infraquanta, such as phonons, spin waves, electron-hole pairs on the Fermi surface of a metal, hydrodynamic mode quanta, etc.:

$$\phi_n = \phi_n \left[1 + \sum_{\nu=1}^{\Lambda/\epsilon_o} \rho_{\nu,n} \, e^{i\nu\epsilon_o t + i\gamma_\nu} (\nu\epsilon_o)^{-1/2} \right] \tag{1}$$

This form includes very small energy losses $h\nu\epsilon_o$ resulting from the spontaneous emission of infraquanta. We have denoted by $\rho_{\nu,n}(\nu\epsilon_o)^{-1/2}$ the amplitude of the component with energy loss $\hbar\nu\epsilon_o$, where $\hbar\epsilon_o = 2\pi\hbar/T_o$ is the energy resolution of the measurement and T_o is its duration. Here γ_ν are random phases and $h\Lambda$ is an upper energy limit which does not exceed the thermal energy of the carriers. The amplitudes are determined by the strength of the coupling αA to infraquanta

$$\rho_{\nu,n} = \sqrt{\alpha A_n} \; \nu^{\alpha A_n/2} \epsilon_o^{1/2} , \tag{2}$$

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and $\alpha A_n \ll 1$ contains contributions from each individual system of infraquanta:

$$\alpha A_n = (\alpha A)_{phot} + (\alpha A)_{phon} + (\alpha A)_{spin} + (\alpha A)_{e-h} + (\alpha A)_{con} \quad (3)$$

where the last three contributions come from spin waves, electron-hole pairs at the metallic Fermi surface, and configurational states or hydrodynamical modes.

The matrix elements $\langle E_n \pm \hbar\omega | Q | E_n \rangle$, where Q is the elementary charge times the sum of the coordinates of all current carriers along the elecric circuit, will all gain the factor in rectangular brackets in Eq. (1). Therefore, the spectral density of the current fluctuations will also gain an additional factor

$$\langle(\delta_n)^2\rangle_\omega = S_{\dot{Q}_n}(\omega) \left[1 + 2 \sum_{\nu=1}^{\Delta/\varepsilon_o} \rho_{\nu n} \cos(\nu\varepsilon_o t + \gamma_\nu)(\nu\varepsilon_o)^{-1/2} \right] , \quad (4)$$

where $S_{\dot{Q}_n}(\omega) = 2g(\omega) \coth(\hbar\omega/2kT)$ is the familiar Nyquist spectrum and $g(\omega)$ is the conductance. This means that the level of thermal noise fluctuates around the Nyquist value with a 1/f spectrum both in current and in voltage, but not in available power, due to the presence of quantum 1/f noise. A formulation of the quantum 1/f noise theory in terms of path integrals was recently given by Widom et al.[4]

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ANY PARTICLE REPRESENTED BY A COHERENT STATE EXHIBITS 1/f NOISE*

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The electromagnetic field of a free electron is best described by a coherent state.[1] However, a coherent state does not have a definite energy, and is therefore nonstationary. Physically this means that there will be quantum fluctuations in the probability distribution and in the current distribution. The main purpose of the present paper is to prove that the spectrum of these fundamental fluctuations, which are part of the definition of a charged particle, is a 1/f spectrum with no lower frequency limit. This proof yields an equivalent formulation of the quantum 1/f noise theory.[2-6]

The proof is composed of three parts. In the first part we prove that the autocorrelation function for the probability distribution in time of a single field mode $\vec{q}$ in a coherent state of amplitude $z_{\vec{q}}$ with $|z_{\vec{p}}|^2 \ll 1$ is

$$A(\tau) = \frac{\pi}{\sqrt{2}} \{1 + 2|z_{\vec{p}}|^2 \cos\omega\tau\},$$

where $\omega = cq$ is the frequency of the mode considered.

In the second part of the amplitude $z_{\vec{q}}$ of the coherent field of

the electron is found to be proportional to $q^{-3/2}$ from lowest-order (in $\alpha = e^2/\hbar c$) perturbation theory.

In the third part, the autocorrelation function for the electron with its field is calculated by taking the product of all autocorrelation functions calculated for individual field modes, again with $|z_{\vec{q}}|^2 \ll 1$, as calculated in the second part. The resulting autocorrelation function is essentially the Fourier transform of 1/f multiplied by $\alpha/\pi = (137\cdot\pi)^{-1}$. As in the diffraction of parcicles, quantum 1/f noise is determined by the behavior of a single particle, but can be observed only with a large number of particles.[5]

*Work performed while visiting the Tokyo Institute of Technology, Japan.

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QUANTUM 1/F NOISE FROM PIEZOELECTRIC COUPLING

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Quantum 1/f noise is a fundamental fluctuation of elementary cross sections and process rates caused by interference between the non-bremsstrahlung component of the scattered beam and various components which have suffered small bremsstrahlung energy losses due to emission of infraquanta with infrared-divergent coupling to the current carriers. Here we consider piezoelectrically coupled phonons as infraquanta.

The interaction Hamiltonian is given by

$$H^1 = (2\pi g/qV)^{1/2}\, \hbar v_s \sum_{\vec{k},\vec{q}} c^+_{\vec{k}+\vec{q}}\, c_{\vec{k}}\, (a_{\vec{q}} - a^+_{\vec{q}}). \tag{1}$$

Here $c_{\vec{k}}$ is the annihilation operator for electrons and $a_{\vec{q}}$ the same for phonons; v_s is the speed of sound and V is the volume of the sample. The dimensionless coupling constant[1] g replaces here the fine structure constant α present in the electrodynamic coupling, and can be calculated in terms of an appropriately averaged piezoelectric constant Q

$$g = \pi C^2 \frac{e^2}{\epsilon\hbar v_s} \frac{Q^2}{\epsilon\rho v_s^2}. \tag{2}$$

Here e is the charge of the electron, ε is the static dielectric constant, ρ the density of the crystal, and C a numerical constant of order unity depending on the crystal structure. For example, for zincblende structures $C = (4/5)^{1/2}$ 0.9. Examples of g-values[1] are: 0.148 for ZnS, 0.018 for CdTe and 4.1 for CdS.

Proceeding exactly as in the case of photons[2-4] we obtain the spectrum of relative fluctuations in the scattering cross section σ

$$\langle\sigma\rangle^{-2} S_\sigma(f) = 2g\cdot A\cdot(f/f_D)^{gA} f^{-1} N^{-1} \qquad (3)$$

where $A = 2(\vec{k}^1-\vec{k})^2/3\pi k_s^2$, f_D is the Debye frequency, $k_s = mv_s/\hbar$ and N is the number of carriers in the sample that yield independent noise contributions. In essence A is the velocity vector change squared, in units of the speed of sound. If all carriers are considered independent, our result is a very large 1/f noise, compared with the Hooge formula prediction. Giant 1/f noise has indeed been observed in piezoelectrics.[5]

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LOW-FREQUENCY CURRENT NOISE AND INTERNAL FRICTION IN SOLIDS

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The theory of the low-frequency fluctuations of charge carriers' mobility and conductivity caused by spontaneous displacements of the defects in solids is developed.It is shown that those relaxation mechanisms of the defects which determine the low-frequency internal friction produce low-frequency current noise too.An example are point defects with symmetry lower than the point symmetry of the crystal.Such defect can be in several states that differ only by their orientation in the lattice.As an alternating stress is applied the transitions between different states of these defects cause internal friction(Snoek's mechanism).The inverse Q-factor is given by

$$Q^{-1} = B \frac{n_d}{kT} \frac{\omega\tau}{1+\omega^2\tau^2} \qquad (1)$$

where n_d is the concentration of the defects,T - temperature, τ- the relaxation (hopping) time,B is of the order of the elastic modulus times the atomic volume squared.

The number of defects with each definite orientation fluctuates around its mean value,n_dV/s,V being the crystal volume,s - the number of different orientations of a defect.These fluctuations cause nonscalar fluctuations of of the resistivity since for a given current direction the carriers are scattered by defects of different orien-

tation in different ways. The spectral density of resistivity fluctuations $\delta\rho_{ij}(\vec{r}_1,t_1)$ and $\delta\rho_{kl}(\vec{r}_2,t_2)$ is given by

$$S_{ijkl}(\vec{r}_1,\vec{r}_2,f) = \delta(\vec{r}_1-\vec{r}_2)\frac{4n_d\tau}{s(1+\omega^2\tau^2)}\sum_{\alpha\beta}\frac{\partial\tilde{\rho}_{ij}}{\partial n_\alpha}\frac{\partial\tilde{\rho}_{kl}}{\partial n_\beta}(\delta_{\alpha\beta}-\frac{1}{s}) \quad (2)$$

Here $\partial\tilde{\rho}_{ij}/\partial n_\alpha$ is the derivative of the anisotropic part of the resistivity with respect to the concentration of defects with a definite orientation α. The spectral density of the voltage noise is

$$S_U(f) = U^2 n_d\, \sigma_s^2\, l^2\, \tau\, /\, V(1+\omega^2\tau^2) \quad (3)$$

where l is the free path length, σ_s - the scattering cross section of the defects. Even for small n_d this noise can be higher than the Nyquist one and the noise caused by temperature fluctuations.

If $\tau = \tau_0\exp(E/kT)$ and the distribution in activation energy E is smooth on the scale kT then on one hand the internal friction spectrum has a background Q_{BG}^{-1} (only slowly depending on ω and T) and on the other hand a current noise with 1/f spectrum is present. The effects are connected :

$$S_U(f)/U^2 \sim (2kTl^2\sigma_s^2/\pi E)\; Q_{BG}^{-1}\; (Vf)^{-1} \quad (4)$$

$Q_{BG}^{-1} \sim 10^{-4} - 10^{-3}$ is usually observed in all metals. Taking typical values of the parameters one obtains the coefficient to $(Vf)^{-1}$ in (4) of the order 10^{-26}-10^{-25} cm^3. This is precisely the magnitude of the coefficient to $(Vf)^{-1}$ usually observed in 1/f noise in metal films.

The spectral density of resistivity fluctuations caused by the migration of the scattering centers randomly distributed in a conductor of a finite volume is also evaluated.

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W E D N E S D A Y   M O R N I N G

ROOM B

QUANTUM NOISE

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INFLUENCE OF NOISE ON THE VOLTAGE VERSUS CURRENT CHARACTERISTICS OF AC-BIASED SQUID MAGNETOMETERS

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Recently we showed[1] that transitions between "winding number" (n) states of a weak link ring are quantum mechanical in origin. With the weak link ring operated in the AC "SQUID" magnetometer mode, this allows us to make definite predictions concerning the AC response of such a magnetometer. Here, we consider the voltage response (V_{OUT}) of a tank circuit-weak link ring combination driven on resonance at frequency $\omega_R/2\pi$ by a current source I_{IN}. We assume that each n-transition has a linewidth Γ($\equiv$ ring inductance Λ/weak link "shunt" resistant R). Each n-transition (with change of enclosed flux) leads to a back emf voltage pulse in the tank circuit. This acts as a narrow band filter so the effect of a succession of voltage pulses can be calculated from standard circuit theory[2], provided the AC flux in the tank circuit coil is linear in I_{IN} between n-transitions. If these transitions commence at a "critical" screening current I_c, then for $I_s \geq I_c$

$$V_{OUT} = Z_1 \, I_{IN} - \frac{\omega_R}{2\pi} \cdot \frac{M}{\Lambda} \cdot \Phi_0 \cdot \frac{1}{1 - i\omega_R\tau} \sum_{\substack{\text{pulses over} \\ \text{one cycle} \\ j}} \sigma_j e^{-i\omega_R t_j} \qquad (1)$$

where Z_1 is renormalized tank circuit impedance $\tau = \Lambda/R$, $\sigma_j = \pm 1$ and the t_j's are the pulse times of the n-transitions.

In figure 1(a) we show a theoretical V_{OUT} versus I_{IN} characteristic for typical SQUID parameters, at a DC bias flux $\Phi_{XDC} = m\Phi_0$ (m integer). Since the shape of this characteristic depends critically on the relative times at which the n-transitions occur, such magnetometers will be extremely sensitive to externally injected flux noise,

particularly at frequencies $\sim \omega_R/2\pi$. In figure 1(b) we show the effects of noise on these characteristics. The "noise" in this simulation is generated using a Poisson distribution for the times at which transitions occur. In figure 2 we show the experimental effects of high frequency noise with frequency components $\sim \omega_R/2\pi$ ($\Phi_{XDC} = m\Phi_0$, $\omega_R/2\pi$ = 430 MHz, flux sensitivity $\approx 10^{-6}\Phi_0/\sqrt{Hz}$). For clarity we show here just part of V_{OUT} versus I_{IN} at different noise levels. We conclude that the "voltage pulse" model of an AC SQUID magnetometer is correct and that the shunt resistor invoked to explain SQUID characteristics is a noise generated artifact.

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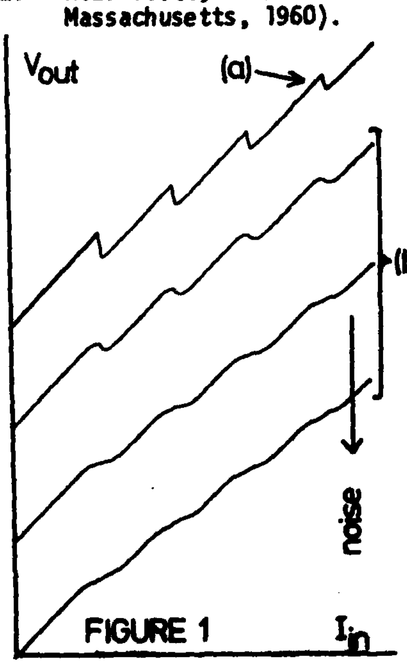

FIGURE 1

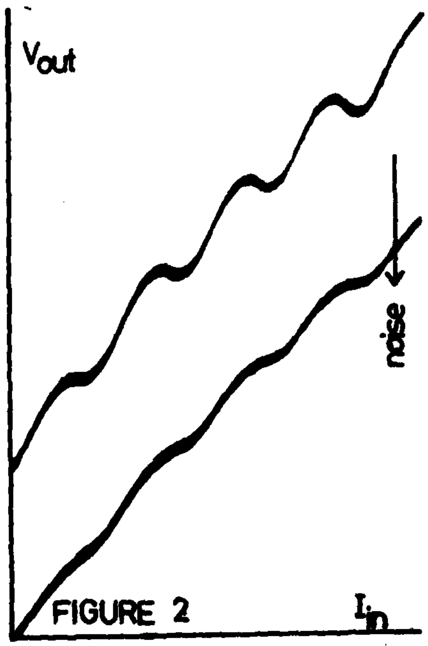

FIGURE 2

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Intrinsic and Extrinsic Noise Sources in an R-SQUID

by

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Several noise sources make significant contributions to the total noise measured in an R-SQUID circuit (the circuit consists of a series connection of a resistor, and inductor and a Josephson junction). The effect of each source must be modelled and verified if the R-SQUID is to be accurately used as an absolute thermometer over the range 0.005 K to 1 K.

The experimental procedure used to measure the circuit noise consists of repeatedly measuring the audio frequency of a signal generated by the Josephson junction (biased by a radio frequency signal) and calculating the variance.

The intrinsic thermal noise generated at audio frequencies by the resistor and by the Josephson junction has been modelled and verified by experiments and reported in a previous noise conference (1).

We treat herein the effects of two extrinsic noise sources, namely "additive" and "mixed-down" noise. The electronic system consisting of the R-SQUID, cooled preamplifier, and room temperature electronics has an overall gain and a finite amplitude signal-to-noise ratio (S/N). The amplitude noise causes the frequency counter to false trigger and thus makes a contribution to the measured variance. We have developed a model for the effect of this additive noise which accounts for the S/N, roll off of the electronic filter, gate time of the frequency counter, the

temperature of the Josephson junction circuit, and other Josephson junction parameters. Experiments bear this model out to within 1% or better, and the effect of additive noise may be reduced to the level of 0.1% under controlled conditions.

External noise may enter the low temperature SQUID circuit via the coaxial cable used to inject the rf bias. Noise at high frequency from the room temperature portion of the coax is mixed down by the Josephson junction into the audio frequency portion of the spectrum and thus makes a contribution to the measured variance. The model we have developed has two sets of limiting conditions: in the first, the variance varies as $J_0^2(x)$; while in the second, the variance is proportional to $J_1^2(x)$. The parameter x is proportional to the injected rf current, and J_0 and J_1 are Bessel functions of order zero and one respectively. Experiments are in very good agreement with these predictions. This effect has ramifications for the performance of the R-SQUID as well as for all rf-biased SQUIDs.

We have found that the thermal noise generated by the Josephson junction, the additive noise, and the mixed-down noise may be accurately modelled and eliminated, thus leaving the Johnson noise of the resistor as the desideratum of the experiment. The evidence suggests that noise thermometry, free from these systematic effects to the level of 0.1%, is within our grasp.

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QUANTUM NOISE LIMIT CONSTRAINTS ON THE PERFORMANCE OF DC SQUID LINEAR AMPLIFIERS

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DC SQUID linear amplifiers fabricated with Josephson tunnel junctions appear to have the potential of approaching the quantum noise limit for an arbitrary linear, phase preserving amplifier. However, in contrast to other more conventional amplifiers, the detailed behavior of the DC SQUID linear amplifier depends not only on the SQUID circuit parameters, but also on the parameters of the linear circuit elements used to couple the SQUID magnetometer to the input source, and the input source impedance itself. As a result, the optimization of the DC SQUID linear amplifier must involve an analysis of the entire circuit. The behavior of the SQUID magnetometer cannot be assumed to be independent of the rest of the circuit as assumed in previous analyses. In this paper, the behavior of the DC SQUID linear amplifier is described in detail as a function of the SQUID and normal circuit element parameters.

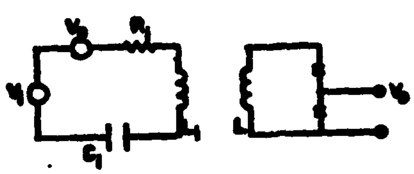

Fig. 1. Lumped circuit element model for the tuned amplifier.

Examples of an inductively coupled tuned amplifier appear in Fig. 1. The input circuit contains the source V_i and the normal coupling coil L_i. The superconducting SQUID loop L contains a pair of Josephson junctions. In most applications, the characteristic times of the input circuit are long compared to the Josephson period. As a result, the subset of the differential equations describing the system which are linear may be integrated. The resultant equations of motion for the quantum mechanical junction phase drops are identical to those of an isolated SQUID with inductance $L_e = L(1-\alpha^2)$, where α is the coupling constant between the SQUID and input loop inductances. Thus, the output signal and noise voltages for the linear amplifier can be directly related to the noise figures and forward transfer function of an isolated SQUID. The well known DC SQUID characteristics are now used to compute the noise temperature contours for the DC SQUID linear amplifier. In addition, the quantum mechanical constraint on the noise temperature of a linear amplifier can now be translated into a constraint on the noise figures of the isolated SQUID, $[(S_V/2LV_\phi^2)(LS_j/2)-S_{Vj}^2/4V_\phi^2)]^{1/2} > \hbar$. In this expression, the output voltage and circulating current noise spectral densities are S_V and S_j, the correlation spectral density is S_{Vj}, and the forward transfer function is V_ϕ.

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QUANTUM, THERMAL AND SHOT NOISE
IN JOSEPHSON-JUNCTION PARAMETRIC AMPLIFIERS AND SQUIDs

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Using a consistent quantum-statistical approach, we have calculated the ultimate sensitivity limits of the Josephson-effect-based amplifiers, imposed by quantum, thermal and shot noise. For the low-frequency amplifiers ("SQUIDs"), both AC and DC types of the devices have been considered, while for the microwave parametric amplifiers only the externally-pumped-junction mode of operation has been analyzed as providing the lowest noise.

For each device, two models of the Josephson junctions have been used. The first one is the generalized Resistively-Shunted-Junction modelwith the equilibrium source of thermal-and-quantum fluctuations, which is quantitatively valid for the externally-shunted Josephson junctions. The second model is given by the Werthamer equations [1]; it describes additional shot-noise contribution to the junction fluctuations, and should be used for the unshunted Josephson tunnel junctions.

Within the frameworks of the both models, in both types of SQUIDs, the minimum value of the generally accepted [2] figure of merit (FOM), the "output" energy sensitivity

$$\varepsilon_V = \langle \delta\Phi_x^2 \rangle / 2L\Delta f, \qquad (1)$$

has been shown to be much less than the Planck's constant $\hbar$. This result does not contradict the uncertainty principle, because ε_V turns out not to be an adequate FOM of SQUIDs as the linear amplifiers.

More adequate FOM for any linear amplifier has been shown to be Θ_N

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which is essentially the amplifier output noise energy, reduced to its input. In the classical limit, $(\Theta_N)_{min}$ is equal just to $k_B T_N$, where T_N is the noise temperature. For a SQUID, Θ_N can be expressed as

$$\Theta_N = \omega(\varepsilon_v \varepsilon_i - \varepsilon_{vi}^2)^{1/2}, \qquad (2)$$

where ε_i and ε_{iv} characterize the SQUID "back-action" noise and its correlation with the output noise, correspondingly [3,4].

For both types of SQUIDs and for the nondegenerate microwave parametric amplifier, the minimum value of Θ_N turns out to be equal just $\hbar/2$, the limit originating from the quantum fluctuations in the device. Nevertheless, in the degenerate mode of operation, Θ_N of any one of the amplifiers can be made much less than the above "quantum limit" even at operation temperatures much higher than $\hbar\omega/k_B$, if only the junction characteristic frequency ω_c is high enough, $\hbar\omega_c \gtrsim k_B T$. We have shown that in SQUIDs such a degenerate mode can be achieved by a simple modification of the SQUID interferometer circuit.

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Vortex Density Fluctuations During Flux Flow in a Type II Superconductor

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The electric field E produced by flux flow in a type-II superconductor is given by the product of density n and velocity v of vortices times the flux quantum ϕ_o . Fluctuations δE there fore are associated in general with those of n and/or v. There are different possibilities for the generation of such fluctuations, a particular one being stochastic relaxation events in the vortex arrangement involving shear processes. Experimental evidence for such a mechanism was obtained by measurements on single crystalline niobium foils with low critical current, on which suitable pinning structures were deposited in form of Nb_3Sn-films using a lithographic proces [1,2] (cf.Fig.1). Fluctuations of the local electric field were found to occur mainly in regions with plastic deformations of the vortex lattice,i.e. regions, where apart from velocity fluctuations, also transients in vortex density are likely to occur.

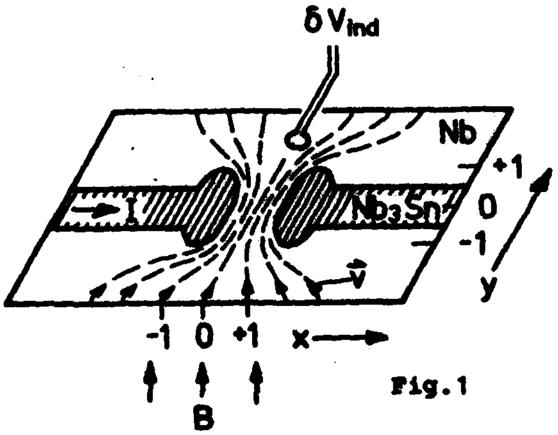

Fig.1

In order to detect the associated fluctuations of flux density δB, a small flat pick-up coil was made whose

position on the sample surface could be varied in a controlled way. The amplified induced signal $\delta V_{ind.}$ was fed to an integrator, whose output then was proportional to $\delta B(t)$.

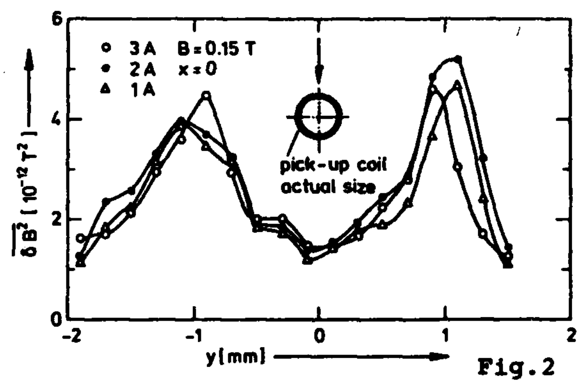

Fig.2

Fig.2 shows $\overline{\delta B^2}$ obtained from such a measurement using the dipole like pinning structure of Fig.1. Data are for three different transport currents I and an average B of 0,15 T. The local dependence of $\overline{\delta B^2}$ ist observed to be quite analogous to that of the electric component δE^2. Time constants derived from $\delta E(t)$ and from $\delta B(t)$ also are seen to obey similar dependences. It is therefore concluded, that the signals δB and δE have the same origin thus providing a means to separate the contributions δn and δv.

Measurements of $\overline{\delta B^2}$ as function of distance z between pick-up coil and sample surface also were performed. From the profiles δB^2 (z), information about the average size of the area, in which a relaxation process takes place, is obtained.

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NOISE SPECTROSCOPY OF A WEAK LINK CONSTRICTION RING

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In the "single particle" ($\psi = |\psi|e^{i\phi}$) view of a thick superconducting ring the phase ϕ is quantised in units of 2π. When the ring is subject to an external flux Φ_x, the energy storage is just $W_n(\Phi_x) = (n\Phi - \Phi_x)^2/2\Lambda$, where n (for $n\cdot 2\pi$) is the ring "winding number", Λ is the ring inductance and $\Phi_0 = h/2e$. A weak link in the ring leads to a finite transition matrix element ($\hbar\Omega/2$) between neighbouring n-states. The Schrödinger equation for the resulting energy levels (bands in Φ_x) is $W_n(\Phi_x)D_n - \hbar\Omega/2(D_{n+1} + D_{n-1}) = ED_n$, where D_n is the amplitude for the ring to have a *winding number n*. In an angular representation $[\psi(\theta) = \sum_n D_n e^{in\phi}]$, this equation reads $(1/2\Lambda)[-i\Phi_0(\partial/\partial\theta) - \Phi_x]^2\psi(\theta) - \hbar\Omega \cos\psi(\theta) = E\psi(\theta)$. The energy band solutions (E_k versus Φ_x) of this equation yield a screening current $J = (-dE_k/d\Phi_x)$ and a ring magnetic moment polarizability $X = \Lambda(dJ/d\Phi_x)$. A more complete description of the ring will include "photon excitations" of frequency $\omega_0^2 = (1/\Lambda_{eff}\, C)$. Here, $1/\Lambda_{eff} = 1/\Lambda + 1/\Lambda_{kin}$, where C and Λ_{kin} are the capacitance and kinetic inductance of the weak link. The Schrödinger equation then becomes

$$(1/2\Lambda)[-i\Phi_0(\partial/\partial\theta - \Phi_x]^2\psi(\theta,m) + m\hbar\omega_0\psi(\theta,m)$$
$$- \hbar \sum_{m'} \Omega_{mm'} \cos\theta\, \psi(\theta,m') = E\psi(\theta,m) \qquad (1)$$

where $\Omega_{mm'}$ is the matrix element for m' photons to go into m photons during a transition between winding number states.

We monitor the energy bands by coupling the ring to a tuned UHF coil of inductance L. For a coil-ring coupling strength K, and coil

noise temperature T_n, the flux noise in the coil is $\langle\Delta\Phi^2\rangle = k_B T_n L [1 + K^2 X]^{(1)}$. In figures 1a and 2a we show, as an example, $\langle\Delta\Phi^2\rangle$ (i.e. X) versus Φ_x for the first and third bands using an extremely sensitive UHF radio receiver. Experimentally, we make band changes by means of small adjustments of the receiver noise temperature. In figures 1b and 2b we show the theoretical best fit curves for X versus Φ_x calculated from equation (1). It is clear that this noise spectroscopy technique provides a direct method of probing the energy levels of a macroscopic quantum object.

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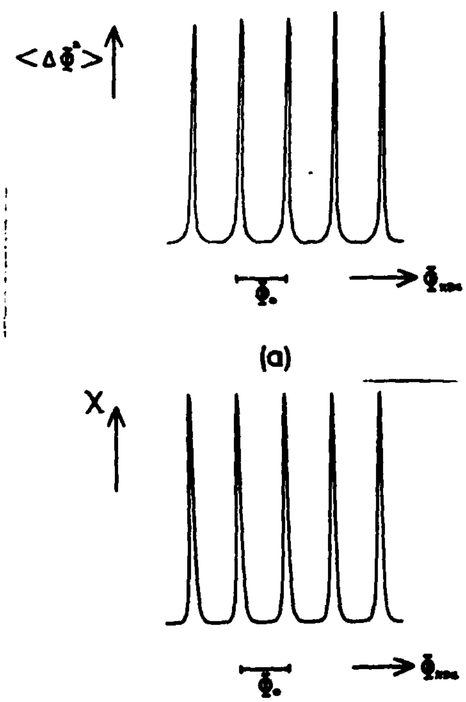

FIGURE 1 (b)

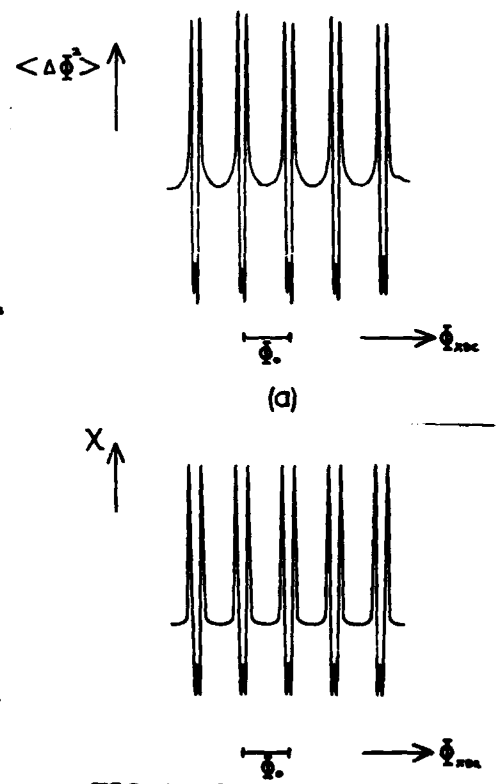

FIGURE 2 (b)

NOISE INCREASE DUE TO FLUCTUATIONS CONVERSION IN SUPERCONDUCTING WEAK LINKS.

Vystavkin A.N., Gubankov V.N., Koshelets V.P., Tarasov M.A.

The broad band voltage noise with spectral density $F_u(\omega)$ at the input of the device with quadratic nonlinearity $I=\beta U^2$ will cause [I] output current noise spectral density $G_i(\omega)$:

$$G_i(\omega)=\beta^2\left\{2\int_0^\infty F_u(\omega+\vartheta)F_u(\vartheta)d\vartheta+\int_0^\omega F_u(\vartheta)F_u(\omega-\vartheta)d\vartheta\right\}$$

The input noise spectrum with central frequency ω_0 and bandwidth $\Delta\omega$ will be converted into ($0 \div \Delta\omega$) low frequency interval and into ($2\omega_0-\Delta\omega \div 2\omega_0+\Delta\omega$)high frequecy interval. For spectral density of wite noise the low frequency part of converted spectrum will be $G_i(\omega)=2\beta^2\sigma^4(\omega_0-\omega)/2\omega_0^2$. At $\omega=0$ it gives $G_i(0)=2\beta^2\sigma^4/\Delta\omega$ where σ is input noise intensity. For $F_u(\omega)$ with components up to $\omega=0$ the output noise spectral density will consist of two parts : $G_i(0)=F_i(0)+2\beta^2\sigma^4/\Delta\omega=F_i(0)\left[I+2S^2R_d^2F_i\Delta\omega\right]=F_i(0)\left[I+4e^3V_{2\Delta}R_d/h^2\omega\right]$ where $\beta=S/R_d=e/(h\omega R_d)$; $F_i=2eI=2eV_{2\Delta}/R_d$; $\sigma_u^2=F_u\Delta\omega=R_d^2F_i\Delta\omega$ were chosen for the case of superconductor-insulator-superconductor (SIS) tunnel junction with responsivity equal to quantum limit. For tunnel junction with $R_n=I0$ Ohm, $\omega=I0^{I0}s^{-I}$, one may calculate $G_i(0)=F_i[I+4,8$ which means that in SIS junction noise spectral density in the region of the highest nonlinearity may exceed the input shot noise density in several times. In Fig.Icurves I(V) and $U_N^2(V)$ at 20 kHz are shown for SIS junction. Noise curve is in good agreement with the previous estimations. For the case of Fig.Ia the junction supercurrent is partially depressed to value $I_c=4\mu A$ and in Fig.Ib supercurrent is depressed to zero value by external magnetic field. The I_c depression causes noise depression at small voltages.

Similar calculations may be carried on for ScN point contacts superconductor-constriction-normal metal. For input shot noise in the case $S=e/kT$;$c=I0^{-I4}$ F we may calculate the output addition to noise $2S^2R_d^2F_i\Delta\omega=4e^3V_\Delta/(ck^2T^2)=0,66$. For Johnson input noise the output noise addition $2S^2F_u\Delta\omega=8e^2/(kTc)=0.35$. This means that shot and Johnson noise converted by nonlinearity exceeds approximately twice the input noise density at low frequencies.

Experimental results of noise measurements in ScN contacts are shown in Fig.2. For $V<\Delta/e$ the main noise source is Johnson noise. Maxima of noise in the region of energy gap coinsides with d^2V/dI^2 maxima.

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AD-A144 388 ABSTRACTS ON THE INTERNATIONAL CONFERENCE ON NOISE IN PHYSICAL SYSTEMS (7..(U) MONTPELLIER-2 UNIV (FRANCE)• 20 MAY 83 2/5

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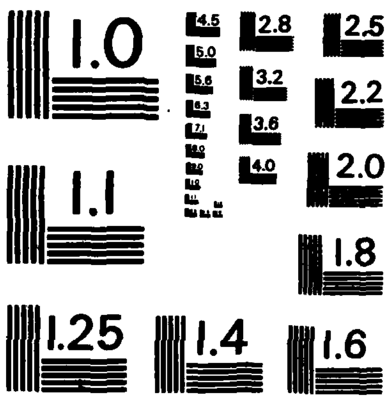

MICROCOPY RESOLUTION TEST CHART
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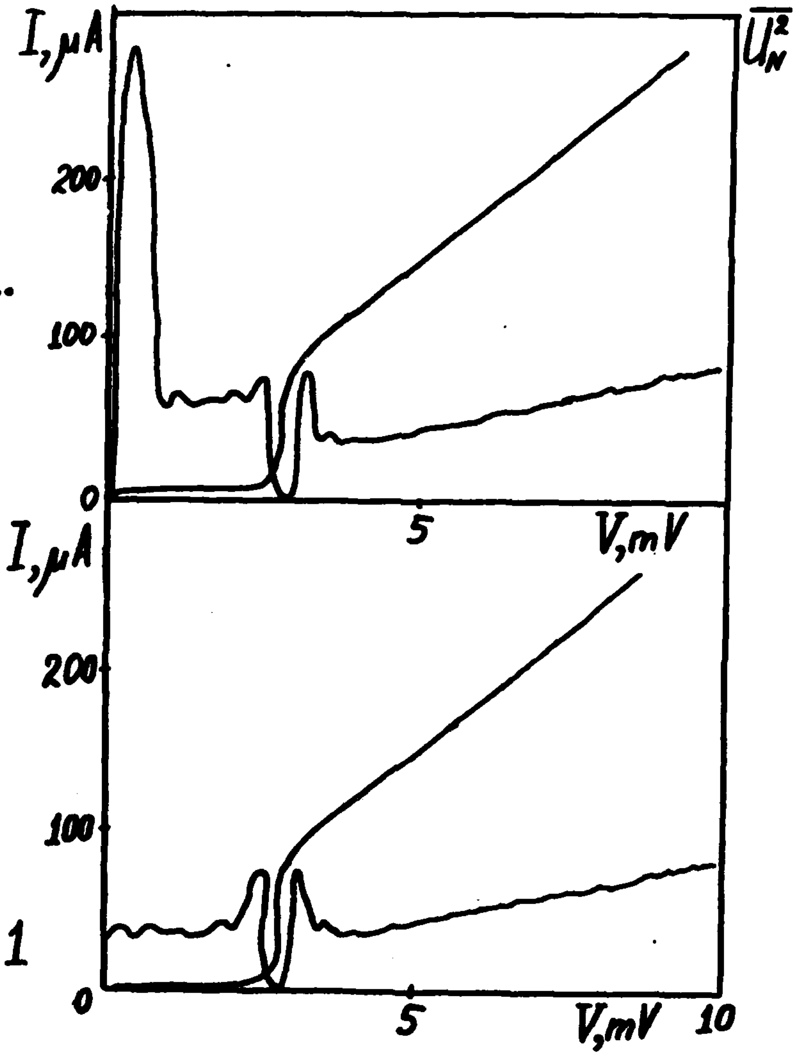
I, μA
$\overline{U_N^2}$
200
100
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a.
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V, mV
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5
V, mV
10

Fig. 1

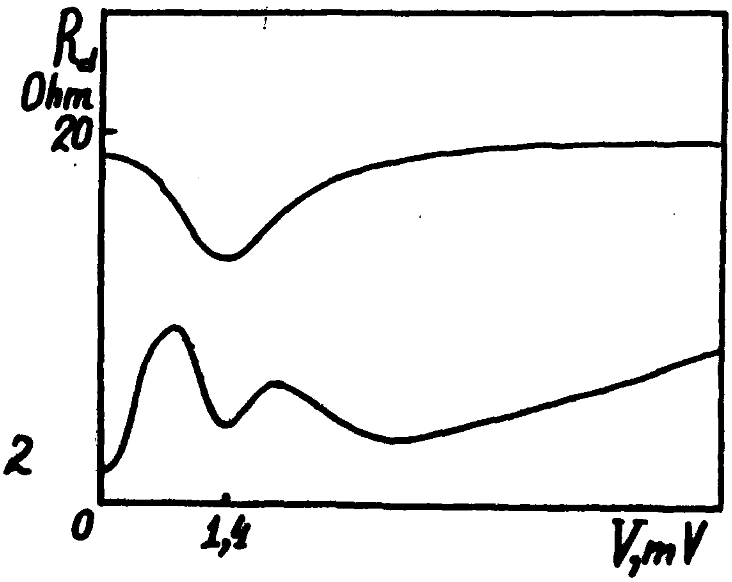
R_d
Ohm
20
0
1,4
V, mV

Fig. 2

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CHAOTIC PHENOMENA IN SUPERCONDUCTING QUANTUM INTERFEROMETERS

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Josephson junction is one of the simplest systems showing chaotic behavior, see, e.g., [1-3]. A little bit more complex system, a single-junction superconducting interferometer, seems more useful to study the conditions of the chaos excitation. Within the framework of the usual RSJ model of the Josephson junction, the RF-driven interferometer is described by the equation

$$\ddot{\phi} + \beta^{-1/2}\,\dot{\phi} + \sin\phi + \phi/l = \rho_0 + \rho_1\cos\Omega t \;. \qquad (1)$$

It is possible to change the degree of nonlinearity of the system by changing the parameter l, the normalized interferometer inductance. At $l \gg 1$, the equation (1) reduces to highly nonlinear equation of a single Josephson junction [1]. On the other hand, at $l \to 0$ the system becomes practically linear.

In our work, the regions of the parameters, for which the interferometer exhibits the chaotic behavior, have been found with the help of a specially designed high-speed electronic analog similator [4]. In the limit $l \to \infty$, our results are in good agreement with the published data for a single Josephson junction. Decrease of the parameter l leads, however, to rapid suppression of the chaos. The most important observation is that at $l<1$ chaos is absent completely for any values of the other parameters, β, ρ_0, ρ_1 and Ω .

The observed boundaries of the chaos excitation regions have been found to be in complete agreement with a very simple criterion suggested by Dr. K. K. Likharev (private communication) for the forced non-

linear-reactance oscillators. According to this criterion, chaos can not occur if the differential reactance is positive during the forced-oscillation process. For a single-junction interferometer, Eq. (1), the condition takes the form

$$\cos[\phi(t)] + 1^{-1} > 0, \tag{2}$$

so that it is always fulfilled at 1<1.

The meaning of the Likharev criterion is that only if the effective reactance for small perturbations becomes negative, the avalanche-type local processes become possible, leading to formation of the strange attractor in the phase space of the system and thus to its chaotic state.

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L1

ANOMALOUS HIGH NOISE IN JOSEPHSON JUNCTION

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In several experiments with Josephson parametric amplifiers of SUPARAMP type the up-normal noise temperatures $\sim 10^4$ K were observed [1]. Such high values can not be explained in terms of the known noise theories. The possible source of this phenomenon is the existence of stohastic oscillations in nonlinear deterministic systems, called "chaos" [2].

The dynamic behavior of an electronic model of unbiased Josephson junction forced by harmonic signal, a model similar to SUPARAMP, was investigated. Mathematical discription of our electronic analog is adequate to resistively-capacitively shunted Josephson junction model.

The spectrum of the junction voltage in a broad range of amplitude I_{rf} and frequency ω of the external signal $I_{rf} \sin\omega t$ was measured. Under certain values of I_{rf} and ω a "chaos", defined as a broad-band noise-rise in the output spectrum, occur (Fig.1). The correlation between "chaotic" states and signal parameters were established (Fig.2). The influence of junction capacitance, characterised by McCumber parameter β_c, on the region of existence of "chaos" was investigated in details.

Thus the anomalous noise-rise may be explained by intrinsic nonlinearity of Josephson junction. The results

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can be used to determine the junction parameters and pumping conditions in real SUPARAMPs.

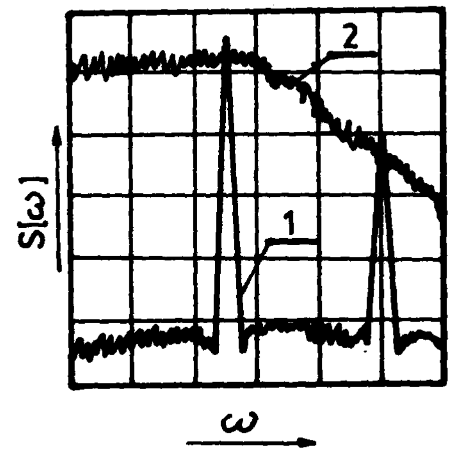

Fig.1 Spectrum of the voltage in case of harmonic (1) and stohastic (2) oscillations, $\beta_c = 17$, $\Omega = 0{,}5$, $i_{rf} = 0{,}7$ (1) and $i_{rf} = 0{,}74$ (2); $\Omega = \omega/\omega_p$, $i_{rf} = I_{rf}/I_o$, $\omega_p^2 = 2eI_o/\hbar C$, I_o - critical current; Vertical 10 dB/div, horizontal 200 Hz/div.

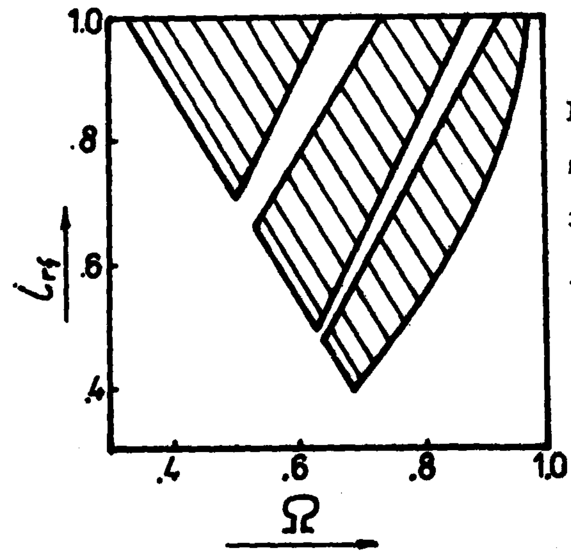

Fig.2 The region of stohastic oscillations in the Ω, i_{rf} plane, $\beta_c = 17$.

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L1

SHOT NOISE AND IT'S CORRELATION WITH JOSEPHSON POINT CONTACTS PARAMETERS AND HEATING.

Vystavkin A.N., Gubankov V.N., Tarasov M.A.

As it was mentioned at [1] the Josephson point contact shot noise intensity for $eV > kT$ depends on diffusion length Λ_e. If $\Lambda_e \gg L$ - contact length, the electrons cross the voltage difference without scattering and get additional energy eV. This additional energy causes the effective carriers temperature increase, which means that noise temperature exceeds physical temperature and causes the shot noise with spectral density $S_1=2eI$. For the contacts with small electron mean free path the electrons obtain only a small part of eV, which causes the difference of noise spectral density from Shottky formula. By the same as for semiconductors in [2] method we may receive for our contacts $S_1=2eIg$, in which $g=2\Lambda/L$.

It must be mentioned that after acceleration in electric field electrons then give back their energy to crystal lattice that causes not only electron gas heating, but also the heating of contact itself. The heating mechanism in ideal Josephson junctions is described in [3]. The temperature in the middle of the junction [3] is $T_m=\left[T^2+3(\frac{eV}{2\pi k})\right]^{\frac{1}{2}}$ where T - physical temperature. This equation means that temperature in the middle of the junction achieves ~70 K for V≈10 mV.

In our experiments we measured $U_n^2(I)$ for f=20 kHz. Dependencies $\frac{dV}{dI}(I), U_n^2(I)$ are shown in Fig.I for Josephson point contact (JPC) in I and II curves, $U_n^2(I)$ for R=30 Ohm at 4.2 K - III curve , noise calculation due to heating - IY curve , and shot noise calculation -Y curve for this point contact. The heating noise (Y curve) gives the higher values than in our experiment. The absence of strong heating is prooved by the hysteresis lack in all our current-voltage curves. The high temperature increase must lead to essential normal resistance increase which was not observed in our experiments, and this is the second proof of the heating lack in JPC.

The dependence of $g(R_N)$ for different JPC is shown in Fig.2. It has simple interpretation - the normal resistance increase is connected with contact length increase and mean free path decrease which leads to parameter g decrease. The R_N increase and g decrease leads to thermal conductivity from contact to bridges decrease due to L increase which must increase heating and Johnson noise in contrast with our experiments where noise decreases with R_N increase. This is additional confirmation of the shot noise model applicability.

The evident dependence of $g(R_N)$ on contact oxidation time may be made from comparison of regions I and II at Fig.2. For oxidation time I5 min g=0.I÷I and for a day oxidation time g=0.0I÷0.I .

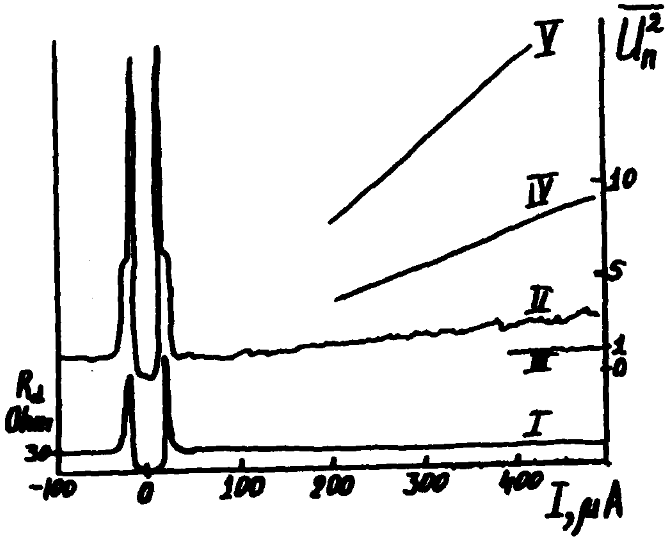

Fig.1

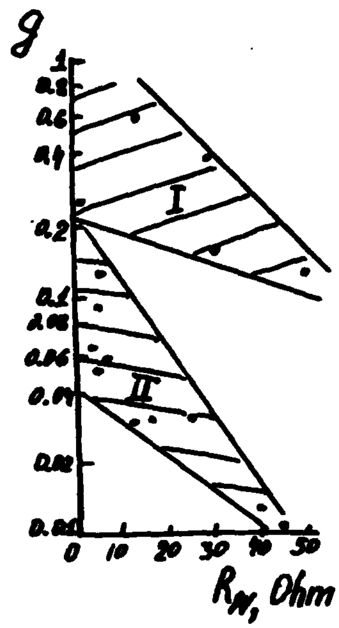

Fig.2

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Invited Paper

1/f Noise in Biological Membranes

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Université Laval, Québec, Canada

Experimental studies of the movement of ionic charges accross biological membranes have shown the existence of stochastic fluctuations of significant magnitude. Although membrane noise was initially considered for its potential effects on encoding of nervous information, more recently it has been used as one of several probes into the the basic mechanisms of conduction of these complex biological devices.

Spectral analysis of such fluctuations, which can be measured either in the form of voltage or current, typically reveals several components: 1/f fluctuations, which appear to reflect diffusion of charge carriers through the restricted pathways of the membrane structure, relaxation (Lorentzian-like) fluctuations which can be linked to elementary 'gating' mechanisms of pathways, 'thermal' background, and instrumentation noise. Unfolding the various components has been a difficult task, considering that several carriers can be simultaneously involved, that the accuracy of the spectral estimates is hampered by limited stability of biological preparations, and that the range over which some important physical parameters (such as temperature) can be varied is quite limited. Nethertheless membrane fluctuations have provided some important data on the size and kinetics of membrane events. The presentation surveys the various aspects involved in membrane noise analysis and outlines its application on a range of biological preparations.

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Observations of low frequency current noise in niobium films-electrodiffusion noise and the absence of 1/f noise.

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We have measured the low frequency current noise from 240 nm thick Nb films in the frequency range 1 mHz $\leq$ f $\leq$ 400 Hz using an AC technique. The power spectral density $S_V(f)$ was found to be proportional to $f^{-3/2}$ at low frequencies, nearly flat between 1 Hz and 10 Hz and then decreased as $f^{-\beta}$, $1 \leq \beta \leq 3/2$ above 10 Hz. Passage of direct current (current density ~10^6 A/cm^2) changed the film resistance in a way suggestive of electrotransport, stabilizing after a few days at 10-20% below its initial value and recovering slowly after the DC field was removed.

AC noise measurements made following extended exposure to the DC bias showed noise power decreased by an order of magnitude at 1 mHz, two orders of magnitude at 1 Hz, and below our sensitivity at higher frequencies. Excess noise present under these conditions is at least two orders of magnitude below the 1/f noise predicted by Hooge's formula[1] and an order of magnitude below that given by the modified formula of Fleetwood and Giordano.[2]

The noise from longitudinal diffusion of hydrogen through the niobium film has been calculated and compared with the data. The low frequency portion of the zero-bias noise and the calculated spectrum have

the same $f^{-3/2}$ dependence and differ by a factor of about five in magnitude, within the uncertainty of estimating the hydrogen concentration and diffusivity. At higher frequencies, the diffusion noise is not readily calculable in our complicated geometry. The weak low-frequency noise with a DC bias is not understood.

The zero-bias noise and resistance of one film has also been measured after heating it to 400°C for several hours in a vacuum. We found that the resistance no longer changed with a DC field and the noise spectrum was similar to the very weak spectrum obtained earlier on extended exposure to a DC field.

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L1

Systematic errors introduced by quantisation in the precise measurement of noise amplitude by digital cross-correlation

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In noise thermometry the most precise way of measuring a noise voltage is to apply it to the paralleled inputs of two independent amplifiers whose outputs are multiplied together or cross-correlated. Noise signals contributed by the amplifiers are uncorrelated and, ideally, the averaged output of the correlator is proportional to the mean square of the input noise signal.

The inaccuracies common to analogue multiplier systems may be avoided by sampling and digitising the outputs of the amplifier channels and performing the multiplications by high-speed digital circuits. The statistical properties of noise signals suggest that a relatively small number of accurately defined digitisation levels may suffice.

For a moderate number $\pm$ K levels the total number of possible products is $4\,K^2$ and it is practicable to compute numerically the expectation of the output as the summation of each possible product multiplied by its probability of occurrence obtained from a bivariate normal distribution function.

The error due to quantisation is found not to depend on x, the rms value of the noise signal being measured, but only on the ratio σ/Δ, where σ is the amplitude of the noise contributed by the amplifiers (assumed equal in amplitude but, of course, uncorrelated) and Δ is the spacing of the quantisation levels.

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For a typical converter spanning ± 8 volts with a total of 32 levels (5 bits, Δ=0.5 V) the following results are obtained for a range of rms input amplitudes and amplifier noise.

x(V)	$\bar{x}^2$	σ=0.125	σ=0.1875	σ=0.2	σ=0.3
0.6	0.36	0.36107423	0.36004915	0.36002288	0.36000001
0.8	0.64	0.64107423	0.64004915	0.64002288	0.64000001
1.0	1.00	1.00107423	1.00004915	1.00002288	1.00000001
1.2	1.44	1.44107423	1.44004915	1.44002288	1.44000001
1.4	1.96	1.96107412	1.96004902	1.96002274	1.95999980
1.6	2.56	2.56106809	2.56004240	2.56001596	2.55999125

The effect of peak clipping is evident for larger values of x. In a typical noise thermometer using this converter σ might be as low as 0.2 and a 6 bit converter with 64 total levels would be preferrable, with the 2x6 bit products conveniently obtainable from a simple ROM.

This numerical approach is expensive in terms of CPU time but allows easy evaluation of the effects of irregularities in the level spacings and weighting of the extreme products to reduce clipping errors.

For uniformly spaced levels in the absence of clipping it is possible to regard the uncorrelated amplifier noise as allowing an effective increase in the resolution of the A/D conversion prior to multiplication and this leads to the following formula which exactly describes the quantisation errors shown in the above table.

$$E\{\tilde{x}^2\} - \bar{x}^2 = \frac{1}{8\pi^2} \exp\left[-4\pi^2 \frac{\sigma^2}{\Delta^2}\right]$$

L1

NOISE IN DIODES AND TRANSISTORS

L1

DETERMINATION OF MICROWAVE NOISE AND GAIN PARAMETERS OF C-BAND GaAs MESFET TROUGH NOISE FIGURE MEASUREMENTS ONLY.

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Abstract

A measuring method for the simultaneous determination of transistor noise and gain parameters through noise figure measurements only is presented, which offers several advantages with respect to conventional measuring methods even if they make use of up-to-date (microprocessor-based) automatic noise and gain meters.

It is based on the Friis' formula:

$$F_m(\Gamma_s, F') = F(\Gamma_s) + (F'(S'_{22}) - 1)/ G_a(\Gamma_s)$$

(F_m, measured noise figure; F and G_a, noise figure and available gain of the device; Γ_s and S'_{22}, noise-source and device-output reflection coefficients; F', second stage noise figure) and on an original method of removing the second stage noise contribution which simultaneously provides the device available gain. After that measurements of F_m are performed for several (redundant, i.e. more than two) values of F' and for several (redundant, i.e. more than four) values of Γ_s, a proper computer-aided data processing procedure furnishes the four noise and the four gain parameters of the device under test. The required set of different values of the second stage noise figure F' is easily obtained making use of a step attenuator inserted after the transistor.

The method, recently developed for bipolar junction transistors up to 4 GHz |1,2|, is applied here for the characterization of GaAs MESFETs above 4 GHz, for which additional problems arise:

- the conditional stability typical of these devices can cause oscillations under conjugate-matched operation. To prevent instability the tuning network at the transistor output port is not used, as it is in conventional measuring systems, and the correct value of $F'(S'_{22})$ is derived by computation from the measured values of $F'(0)$ and S'_{22}.

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- the low level of noise generated by the device requires higher accuracy in the measurement of F_m by evaluating also the noise of those stages of the measuring system usually considered lossless, as the input tuner used as admittance transformer and the input bias network of the transistor;

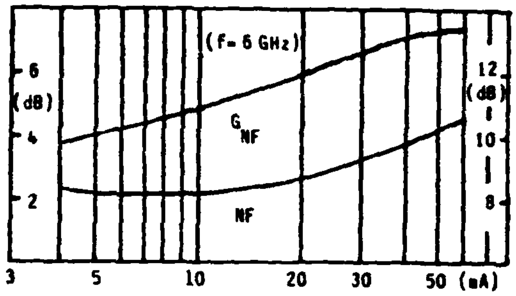

Fig.1 - Minimum noise figure and associated gain of NE24483 vs.drain current (V_{DS} = 3 V, T = 290 °K).

- due to the increased requirement in overall accuracy, appropriate criteria for the selection of the Γ_s values must be added to those already suggested for the case of bipolar transistors |3,4|.

In this paper are also reported:

- a detailed description of all the subsystems of the measuring set-up that are used to measure F_m, F', Γ_s, S'_{22}; to prevent (and monitor) oscillations; to monitor power levels and prevent saturation; etc.;
- step-by-step suggestions on how to carry out experiments and some additional measurements to check the correctness of the results;
- a discussion on accuracy;
- informations on the computer-aided data processing procedure;
- indications for a computer-controlled version of the measuring set-up.

As experimental verification, the noise and gain parameters of a GaAs MESFET (NE 24483) as function of the operating parameters (frequency, drain current and temperature) are presented. A little example is shown in Fig.1 .

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L1

Generation - Recombination Noise in Si JFETs

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The theory of generation - recombination noise (g-r) in Junction Field-Effect Transistors (JFETs) is well known and has been outlined by several authors (1,2). The noise is presumed caused by fluctuation of the charged state of shockley-Read-Hall (SRH) centres in the space charge region of the device. We have measured the equivalent noise voltage in low noise n-channel silicon JFETs operated in the saturation region. Measurements have been made in the frequency range 10Hz to 100kHz and in the temperature range 100K to 360K on devices from several processing batches and with various bias conditions. The data indicates that the dominant source of excess noise in the devices is of the g-r type. Two distinct maxima appear in the noise-temperature curve at 10Hz, one at 165K and the other near room temperature. This indicates the presence of two discrete energy levels deep in the gap. Analysis of the data is presented and compared to the g-r theory. Also comparison with DLTS measurements on the same samples will be presented.

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JFET GATE-CURRENT NOISE

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Noise generated within a junction field-effect transistor (JFET) can be replaced by an equivalent series input voltage noise source and an equivalent parallel input noise source. The voltage source represents the noise sources which produce fluctuations in the channel. The current source represents the fluctuations in the gate current.

The gate current noise has been studied over a frequency range 0.2 Hz-10 kHz using a capacitive feedback technique with a limit given by an equivalent shot noise source of 5.0×10^{-13} amps. The observed current noise exhibits the white shot noise of the gate current. This current is made up of two components, the gate-channel diode reverse biased leakage current and the channel carrier impact-ionization current.

The devices were experimental versions of BF800 and BF818, biased well above pinch-off. Impact ionization current appears when the electric field across the pinch-off depletion region accelerates the carriers in the channel sufficiently to generate electron-hole pairs. The minority carrier of this pair is swept into the gate-channel depletion region to give an extra gate current component[1]. The gate current increased rapidly above 7 volts (Figure 1).

The current noise spectra are shown in figure 2. Where the current is dominated by impact ionisation current the spectrum is white but an excess component is observed for currents which are largely leakage.

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This work was supported in part by Thorn-EMI and SERC.

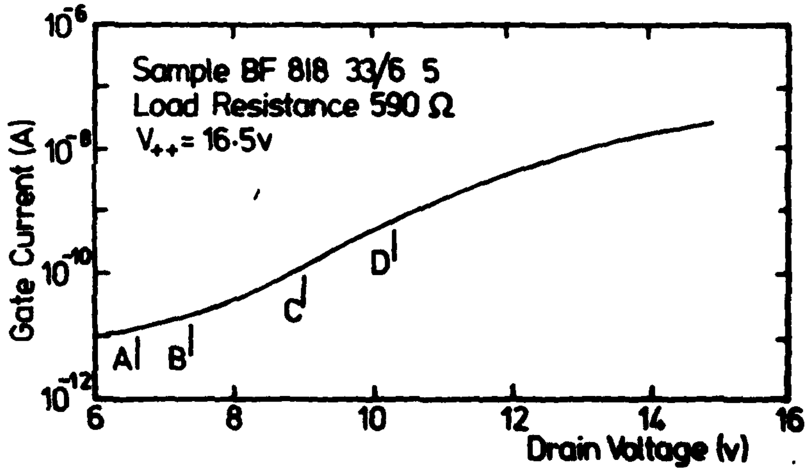

Figure 1. Gate Current against Drain Voltage along Load Line

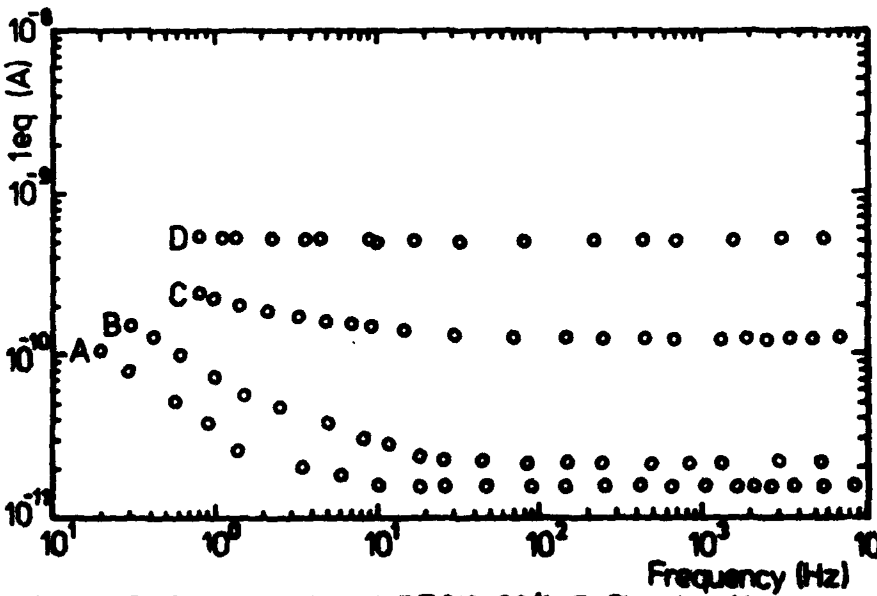

Figure 2. Current Noise of BF 818 33/6 5, Showing V_{DS} Dependence.

L1

Noise and input admittance of HEMTs

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Since the high electron mobility transistor (HEMT) is an FET, the noise is thermal noise in the channel. The only difference with a MOSFET is that saturation effects are treated differently. It is assumed that the channel mobility μ is constant up to a critical field strength E_c and that the drift velocity $U_d=\mu E$ saturates at the drain to the value $U_c=\mu E_c$ at $E=E_c$. This yields

$$I_d = I_{ds} = \mu wC_2(V_g-V_{off}-V_{ds})E_c = \frac{\mu wC_2}{L}\left[(V_g-V_{off})V_{ds}-\frac{1}{2}V_{ds}^2\right] \qquad (1)$$

Solving for V_{ds} yields

$$z_s = \frac{V_{ds}}{V_g-V_{off}} = 1+a-(1+a^2)^{1/2}\ ;\ a=\frac{E_cL}{V_g-V_{off}} \qquad (1a)$$

Here C_2 is the capacitance per unit area between gate and channel.

The drain noise is identical with a MOSFET:

$$S_{I_d}(f) = 4kTg_{do}\,\gamma_1(z);\ \gamma_1(z) = \frac{1-z+\frac{1}{3}z^2}{1-\frac{1}{2}z} \qquad (2)$$

where $g_{do} = \mu wC_2(V_g-V_{off})/L$ and $z=V_d/(V_g-V_{off})$.

A channel noise emf Δu_{xo} at between x_o and $(x_o+\Delta x_o)$ gives rise to an induced gate current

$$\Delta i_g = j\omega wC_2\frac{g(V_o)\Delta u_{xo}}{L}\left[\int_0^L\frac{x\,dx}{g(V_o)} - L\int_{x_o}^L\frac{dx}{g(V_o)}\right] \qquad (3)$$

Carrying out the integration, taking mean square values and integrating with respect to the device length L yields (2) and

$$S_{I_g}(f) = \frac{4kT\omega^2C_{do}^2}{g_{do}}\,\gamma_2(z);\ \gamma_2(z) = \frac{8(2z^4-18z^3+63z^2-90z+45)}{135\,(2-z)^4} \qquad (3a)$$

L1

$$S_{I_g, I_d}(f) = 4kTj\omega C_{do}\gamma_3(z); \ \gamma_3(z) = \frac{z(z^2-6z+6)}{9(2-z)^3} \tag{3b}$$

where C_{do} is the device capacitance at zero drains bias.

By writing down the wave equation

$$\frac{d^2}{dx^2}\,|g(V)\Delta V(x)| = j\omega C_2\Delta V(x) \tag{4}$$

where $\Delta V(x)$ is the a.c. amplitude of the channel voltage at x due to an a.c. emf ΔV_g at the gate and subtituting

$$\Delta V(x) = \Delta V_o(x) + j\omega\Delta V_1(x) + (j\omega)^2\Delta V_2(x)+\ldots \tag{4a}$$

one can show that the gate conductance g_{gs} is

$$g_{gs} = -\frac{\omega^2 C_2 w}{\Delta V_g}\int_0^L \Delta V_1(x)dx) \tag{5}$$

Solving $\Delta V_1(x)$ and carrying out the integration yields

$$g_{gs} = \frac{\omega^2 C_{do}{}^2}{g_{do}}\gamma_6(z);\gamma_6(z) = \frac{(\frac{1}{12} - \frac{1}{6}z + \frac{9}{80}z^2 - \frac{7}{240}z^3 + \frac{1}{360}z^4)}{(1 - \frac{1}{2}z)^5} \tag{5a}$$

With the help of Eqs (2), (3a) and (5a) the minimum noise figure F_{min} can be evaluated over a wide frequency range.

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L1

MICROSCOPIC ENERGY CONSERVING SIMULATION OF MULTIPLICATION NOISE

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To date, the multiplication process in avalanche devices (Impatt-photodiode) have been mainly analyzed with continuous device physics [1]. In very short avalanche regions, it has been demonstrated [2] [3] that the threshold energies for ionization and the non stationary hot carrier transport could affect the noise properties and, therefore, the existing theories fail.

The aim of this paper is to propose a realistic simulation of the impact ionization in precisely these ultra short avalanche regions. The difficulty of incorporing the new features, which are not taken into account in the previous theories was overcome by performing an energy conserving computer simulation. The motion of each carrier (holes and electrons) is studied by considering the scattering process and the ionizing collision which are assumed function of the energy of each particle. When impact ionization occurs, the energy is reinitialized to an energy close to the bottom of the conduction band. Moreover, Poisson's equation is solved to provide the electric field acting on the carriers. We use this method to determine all the fluctuations due to the ionization process.

Results of the program for some cases have been compared to previous analyses [1]. In fig. 1, the variations of the particle current versus time for a p-i-n like diode ($Nd = 10^{15}$ At/cm^3) is schown. The time serie is of 100 ps and the sampling time of 5×10^{-2} ps. The DC current multiplication is 10. In fig. 2, the temporal autocorrelation function of the particle current is given. The fluctuations are found to decay in a time of the order of several picoseconds. Of particular interest is the variance of the current fluctuations versus the multiplication factor M. The results obtained are in good agreement with existing theories [1].

This method will be applied to ultra short multiplicative structure < 0.1 µm and will enable us to obtain some insight into how the carrier multiplication noise is influenced by the non stationary ionization process.

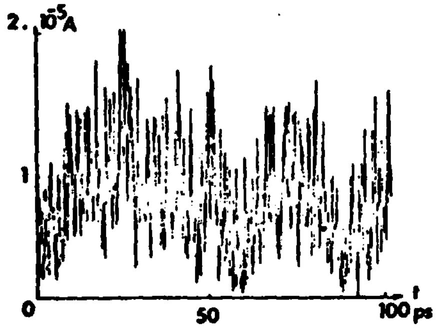

Fig. 1
Variation of the particle current versus time
p-i-n GaAs diode
(Nd=10^{15}at./cm^3,L=0.2μm)

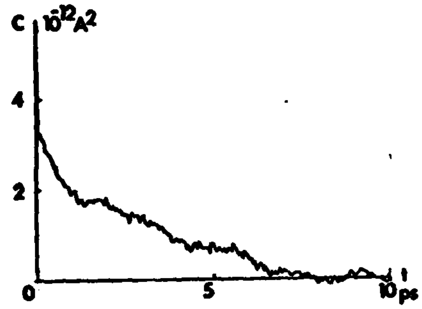

Fig. 2
The autocorrelation function of the fluctuations in this current

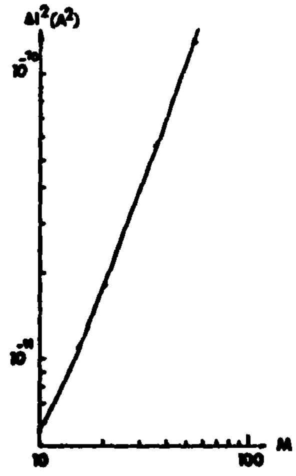

Fig. 3
The variance of the current fluctuations vs the multiplication factor M

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WEDNESDAY AFTERNOON

ROOM B

THEORY 1/f NOISE

L1

SOFT PHOTON ORIGIN OF 1/f NOISE IN ELECTRICAL CIRCUITS

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and A. Widom, G. Megaloudis, G. Pancheri and Y. Srivastava
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In the context of the quantum electronic Brownian motion problem, Handel[1] introduced the notion that soft photon emission can play an important role in noise processes. In the mathematical formulation of the general quantum Brownian motion problem[2], direct application can be made to both quantum field theory and the quantum electro-dynamic engineering of electrical circuits. Within the "no-recoil" methods of quantum field theory, the Feynman diagrams for multiple photon emission can be classified to all orders in $\alpha = e^2/hc$ given the inherent quantum fluctuations in the electronic currents due to purely condensed matter motions. In this paper we make the above statements concrete[3,4], using a model of quantum electronic shot noise devices which is in common use. Thus, if the renormalisation of the shot noise device conductance to be considered is as depicted in figures 1a and b, and if $Y(\zeta)$ and $y(\zeta)$ denote, respectively, the photon renormalised and purely condensed matter admittances of a shot noise device, i.e. the conductance functions are defined

$$G(\omega) = \mathrm{Re}Y(\omega + i0^+) \tag{1}$$

and $$g(\omega) = \mathrm{Re}y(\omega + i0^+) \tag{2}$$

then within the "no-recoil" approximation of quantum field theory we show as our central result that

$$G(\omega) = \int_0^\omega dP(\Omega)[(\omega/\Omega) - 1]\, g(\omega - \Omega). \tag{3}$$

Here, $dP(\Omega)$ is the probability that the soft photon radiation energy in figure 1b lies in the interval $\hbar d\Omega$. The renormalised coupling

(β-function) due to coupling in α and the engineering radiative impedances generally enter into $dP(\Omega)$ in the form

$$dP(\Omega) = \beta(\Omega\tau^*)^\beta \, (d\Omega/\Omega), \; \Omega\tau^* << 1 \qquad (4)$$

where τ^* is the internal time scale of the device.

We provide two specific examples of the method by which we can incorporate the soft photon renormalisation into the engineering conductance of circuit elements. We consider first a single electron tunnelling device and second a series of LCR resonant circuit. We present preliminary experimental data on high 'Q' superconducting resonant cavities which support our theoretical soft photon mechanism for the generation of 1/f noise in electrical circuits.

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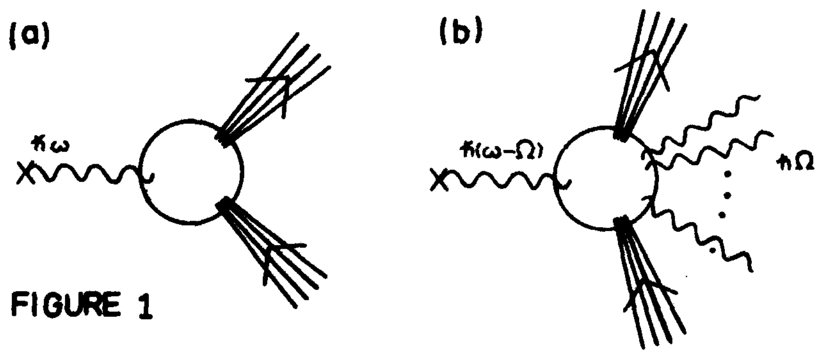

FIGURE 1

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DIRECT CALCULATION OF THE SCHRÖDINGER FIELD WHICH GENERATES QUANTUM 1/F NOISE

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The starting point of the quantum 1/f noise theory[1-5] was the expression of the scattered wave

$$\phi = e^{i(\vec{p}\vec{r} - Et)/\hbar} \left[1 + (\alpha A)^{1/2} \int_{\hbar\omega_o}^{\hbar\omega_1} e^{i\varepsilon t/\hbar} \, e^{i\gamma_\varepsilon} \, \varepsilon^{-1/2} d\varepsilon \right] \qquad (1)$$

in which the second term in rectangular brackets represents the partial waves with energy loss ε due to bremsstrahlung and ω_o is the frequency resolution limited by the duration of the noise measurement T: $\omega_o = 2\pi\hbar/T$. Bremsstrahlung means here emission of infraquanta of any nature with infrarent-divergent coupling to the charge carriers, such as photons, phonons, spin waves, electron-hole pairs at the Fermi surface of a metal, hydrodynamic excitation quanta, etc. For the case of photons $\alpha A \equiv (2\alpha/e\pi)(\Delta\vec{v}/c)^2$, where $\alpha = 1/137$ is the fine structure constant and $\Delta\vec{v}$ is the velocity change of the carriers in the scattering process, while c is the speed of light. The upper limit $\hbar\omega_1$ of energy losses is given by the kinetic energy of the carriers.

The present calculation starts from a solution of the Schrödinger equation in the presence of both an electromagnetic field $\vec{A} = \vec{a} \cos(\omega t + \gamma)$ and an arbitrary scattering potential $V(\vec{r})$

$$(1/2\, m)\, (-i\hbar\nabla - e\vec{A}/c)^2\, \phi + V\phi = i\hbar\dot{\phi} \qquad (2)$$

in terms of the Green's function G of the equation with $V = 0$. This formal solution is an integral equation which can be iterated. The first approximation is the Born approximation, linear in $V(r)$. Taking a Fourier expansion of G in time, we obtain the scattering amplitudes with simultaneous emission of n photons in terms of the nth-order Bessel functions, and the scattered Schrödinger field ψ_{sc}, constructed with the Green's function method. The current density corresponding to this field is found to be

$$(e/m)\vec{p}|\psi_{sc}|^2 = (e/m)\vec{p}(|a|^2/r^2)\ [\ 1 + \sum_{\vec{k},s} \beta_{\vec{k},s} \cos \omega_{\vec{k}} t + \gamma_{\vec{k},s}\ ]\ , \quad (3)$$

where $\beta_{\vec{k},s} = -e(\vec{p}-\vec{p}_o)\cdot\vec{a}_{\vec{k},s}/mch\omega$. Here $\vec{p}$ is the momentum of the scattered carriers, $\vec{p}_o$ their initial momentum, m their mass, and $\vec{a}_{\vec{k},s}$ is the amplitude of the vector potential $\hat{A}_{\vec{k},s}$ in the field mode of wave-vector $\vec{k}$ and polarization s. Although our result in Eq. (3) is not identical to $(e/m)\vec{p}|\psi|^2$ given by Eq. (1), it yields exactly the same autocorrelation function and ω^{-1} spectral density as Eq. (1). The only difference is the presence of a three-dimensional (lattice sum) in Eq. (3), while the original form (1) contains an equivalent one-dimensional substitute. This verifies the applicability of Eq. (1) as the basis of the quantum 1/f noise theory while also pointing out what the more exact expression is.

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1/f NOISE IN PHYSICAL AND CHEMICAL SYSTEMS

L1

MEASUREMENTS OF 1/f NOISE IN JOSEPHSON JUNCTIONS

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The 1/f voltage noise across current-biased resistively-shunted Josephson junctions has been investigated. Measurements verified that the fluctuating parameter was the critical current and its spatial correlation length was less the about 1 micron. The temperature dependence of the noise was also measured.

The junctions were fabricated for digital applications at IBM. They have a Pb-In-Au base electrode, a circular 2.5 micron tunnel barrier formed during RF oxidation, and a Pb-Bi counter electrode. The critical current was typically 20 microamps and shunt resistance 3 ohms. The 1/f fluctuations are measured using an RF SQUID. A magnetic field can be applied in the plane of the junction.

The magnitude of the 1/f voltage noise across the junction was measured as a function of bias current. The measured dependence was exactly that predicted by the RSJ model, in the limit of negligible quasipartice condunctance, when the dominate fluctuating parameter is the critical current.

The magnitude of the junction critical current in a magnetic field agrees well with the predicted diffraction pattern for a circular junction. As the magnetic flux in the barrier increases, the instantaneous phase difference goes from being constant across the junction to oscillating rapidly as a function of position. When the characteristic

scale of these oscillations becomes less than the spatial correlation length of the critical current fluctuations, the total critical current noise summed over the entire junction will rapidly vanish. The measured 1/f noise does not vanish as the critical current goes to zero, as predicted by the thermal fluctuation model. It scales well with a model where the noise is not spatially correlated over distances greater than about 1 micron or less.

The temperature dependence of the noise magnitude and slope on a log-log plot was measured. The magnitude and slope at 10 Hz changed from $10^{-20} Amps^2/Hz$ and -.95 at 4.2 K to $5 \times 10^{-21} Amps^2/Hz$ and -1.1 at 1.8 K. This behavior can be interpreted as resulting from a process having a time constant of approximately a microsecond multiplied by an exponential factor, i.e. $\tau = \tau_o \exp(E_i/kT)$, where E_i has a gaussian distribution centered at about 2.6 meV and a FWHM of about 1 meV. These activation energies could be attributed to oxide defect states in the tunnel barrier.

1/f Noise fluctuations in α-particle radioactive decay of 95 Americium 241. J. Gong, C.M. Van Vliet, W.H. Ellis, G. Bosman, and P.H. Handel, Departments of Electrical Engineering and Nuclear Sciences, University of Florida, Gainesville.

Alpha particles from $_{95}Am^{241}$, decaying to $_{93}Np^{237}$, with a half life of 458 years at a peak energy of 5.48 MeV, were counted with a reverse biased silicon surface barrier detector, followed by an ND 575 analog to digital converter and an ND 66 multichannel analyzer. The count was kept under 1000 counts/sec, so no dead time corrections were necessary. The Allan variance $\sigma^{A2}(T)$ was determined, as well as the usual variance, for counting times of 1 to 1000 minutes. While the usual variance fluctuated ("variance noise") at long-time intervals, the Allan variance converged to a stable value when the number of adjacent intervals was thirty to sixty. For the longer time intervals, several measurement series had to be averaged by normalizing to an average count of 18,000/min. The results thus obtained for the Allan variance $\sigma^{A2}(T)$ and the relative Allan variance $R(T) = \sigma^{A2}(T)/\langle M_T\rangle^2$, where M_T is the count in an interval T, are shown in Figs. 1 and 2.

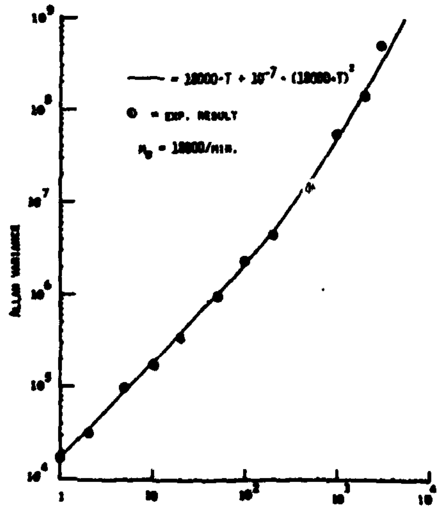

Fig. 1

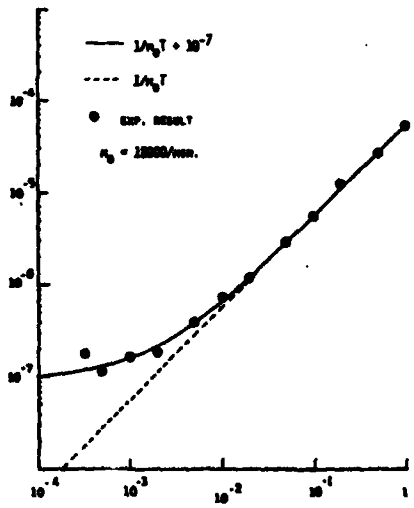

Fig. 2

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The curves are fit to the theoretical expressions

$$\sigma^{A2}(T) = 18{,}000\ T + (18{,}000)^2\ 10^{-7}\ T^2,\ T \text{ in minutes;}$$

$$R(T) = 1/18{,}000\ T + 10^{-7},\ T \text{ in minutes.}$$

The deviation from T, or T^{-1} behavior, respectively, indicates the deviation from Poisson statistics, due to 1/f noise. According to theory (see abstract on Allan variance theorem), the flicker floor is

$$R(T_\infty) = 2\,C \log 2 = 10^{-7},$$

where C is the relative magnitude of the emission 1/f noise, $S_m(\omega) = C\,m_0^2/2\pi\omega$, where m_0 is the average counting rate. The results are compared with Handel's theory of quantum 1/f noise[1-3]. According to this theory we obtain a flicker floor of

$$R(T_\infty) = 4\zeta \cdot (8.32 \times 10^{-7})\,E \log 2/\varepsilon$$

where E is in MeV, ζ is a coherence factor, and ε is the dielectric constant of Am O_2 (about 20). This matches the experimental data for $\zeta = 0.2$. We believe these measurements are the first experimental confirmation of the bremstrahlung mechanism, causing 1/f noise due to beats of the inelastically scattered wave packet components, as proposed by Handel. It also indicates that radioactive decay is not the "exemple par excellence" of Poisson statistics, as claimed by many textbooks.

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L1

NOISE IN ELECTROCHEMICAL SYSTEMS

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The stochastic behavior of a metal-electrolyte interface can be analyzed by measuring the electrochemical noise-i.e. the random fluctuations of the current (potential) flowing through the interface when the potential (current) is maintained constant. This allows a new approach of the kinetics of the interfacial reaction mechanisms to be achieved. New informations which would not be accessible (or only accessible with difficulty) by deterministic techniques (current-voltage curves, transient response, impedances ...) should be obtained by this way.

In addition the measurement of the electrochemical noise avoids interface alteration due to too large amplitude of a perturbating signal inherent to any relaxation techniques. Hence a simple "listening" of the system is performed without any external perturbation.

Measurement arrangement

The power spectral density (p.s.d.) of the electrochemical noise $\underline{v}$ is measured through the crossspectrum ϕ_{xy} of the outputs x and y of two identical amplification channels whose parasitic noises (n_x and n_y) are independent.(fig.1). The arrangement based on a Hewlett-Packard 5451C Fourier analyzer allows a 1 Hz-50 kHz frequency range to be analyzed. To obtain the original electrochemical noise the controller (potentiostat or galvanostat) noise has to be taken into account.

Examples

The noise generated by the silver electrodeposition in perchlo-

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ric medium is given in fig. 2. The observed p.s.d. is interpreted by a shot noise which can be related to nucleation-growth processes.

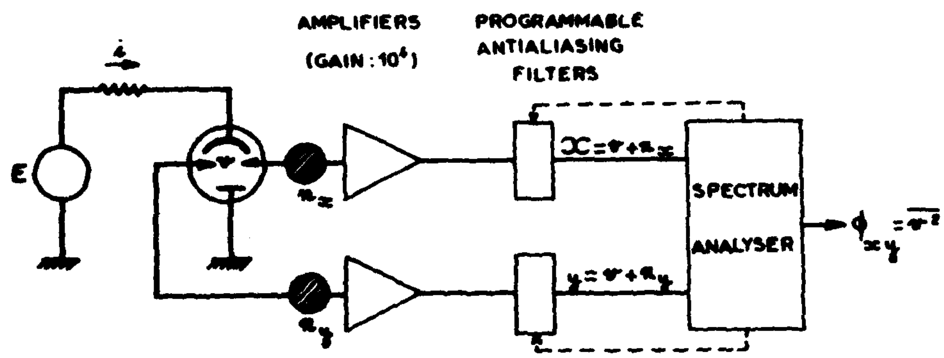

Fig. 1 : Experimental arrangement used for measuring the voltage noise v (n_x and n_y are parasitic noises generated by the amplification channels).

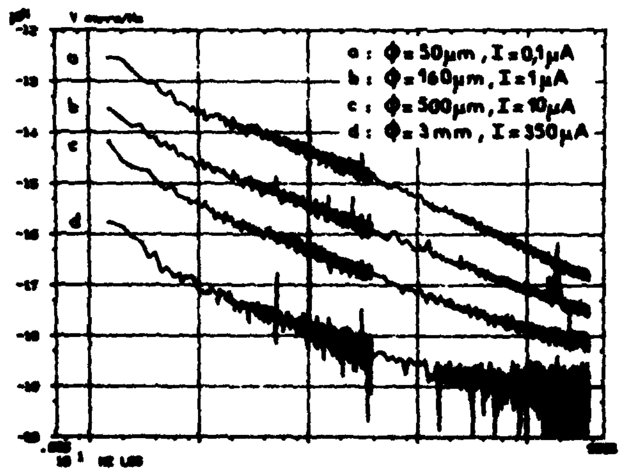

Fig. 2 : Electrocrystallisation of silver in perchloric solution. Power spectral density of the voltage fluctuations for various electrode areas at 5 mA.cm² current density.

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1/f Noise in Aqueous $CuSO_4$ Solution

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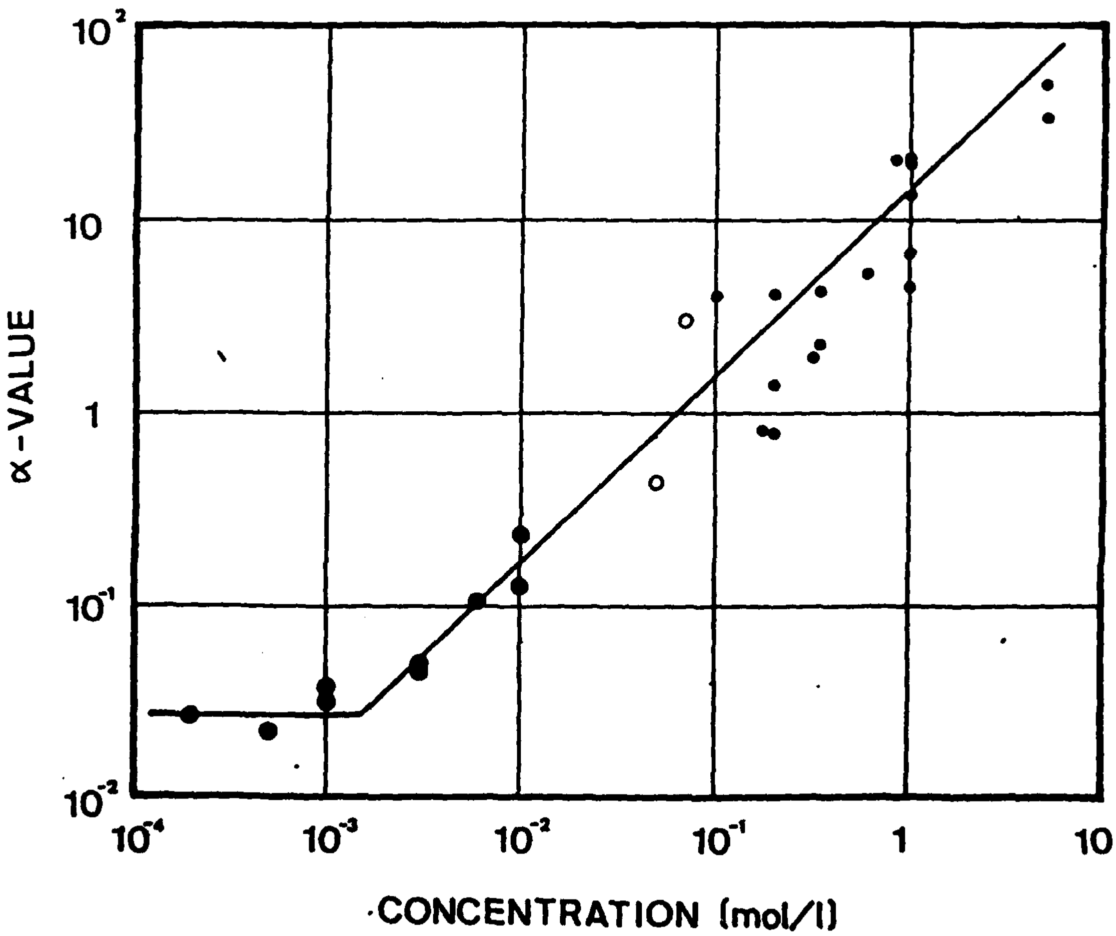
Conductance fluctuations of $CuSO_4$ aqueous ionic solutions through a hole (diameter is about 10 microns) made in a thin diaphragm separating two compartments were observed over ion concentrations from 5×10^{-4} to 10^{-2} mol/l. It is found that the power spectral density is approximately proportional to 1/f for ion drift velocities smaller than a critical value which is of the order of 10^{-3} m/s. Above this value the power spectral density of the conductance fluctuation approaches a Lorentzian form. The α-value of the 1/f fluctuation is approximately proportional to the ion concentration when the ion concentration is larger than 10^{-3} mol/l as was already observed by Hooge and Gaal. Below this critical value, however, the α-value approaches a constant value of 2.5×10^{-2}. The observed dependence of the α-value on the ion concentration is plotted in Fig.1. The fact that the α-value is proportional to the ion concentration suggests that, provided the conductance fluctuation is attributable to the mobility fluctuation, the local ion mobility of water fluctuates

and the fluctuation has a spatial coherence length which is independent of the ion concentration. This coherence length is estimated to be equal to the mean distance between ions at the critical ion concentration below which the observed α-value becomes independent of the ion concentration. This value is 10 nm.



L1

ELECTRICAL RESISTIVITY FLUCTUATIONS IN KCL SOLUTIONS

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In the search for the physical mechanism of 1/f noise in electrolytes we investigated resistivity fluctuations in aqueous and non-aqueous KCl solutions. In the frequency range from 0.05-5000 Hz our samples do not show 1/f noise. Instead the fluctuations in excess of thermal noise are characterized by spectra which are flat at low frequencies. Voltage fluctuations were measured under constant current through single cylindrical glass micro-capillaries (length ≈ diameter) connecting two compartments, filled with the same electrolyte. The shape of the observed spectral densities depended on fluid flow induced either by an applied electric field (electro-osmosis) or a pressure difference (1,2). The noise is apparently due to concentration fluctuations as the magnitude of the measured variances of the voltage fluctuations are in good agreement with the variances calculated from concentration fluctuations as the sole noise source (3).

To explain the shape of the spectra we utilize a one-dimensional model. The calculations are based on a linearized convective diffusion equation for concentration fluctuations in the charge neutrality approximation. The spectral densities are averaged over the distribution of flow velocities

in our capillaries. We have made detailed comparisons between the calculated and experimental spectra. The agreement is good indicating that this simple model already contains the essential physics to explain our experimental results.

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THURSDAY MORNING

ROOM A

L1

Invited Paper

PHASE AND FREQUENCY NOISES IN OSCILLATORS

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SUMMARY

The behavior of oscillators is perturbed by noise sources localized in sustaining circuits and buffer amplifiers, and in the resonator (or in the equivalent delay line or phase shifter).

Among these differend sources can be distinguished internal and external noises, respectively generated in the oscillation loop and in the output circuits.

Also distinction is made between additional noise, which is directly added to the signal, and parametric noise, which acts on the elements defining the frequency or the phase of the oscillator.

These different noise sources are reviewed. Their influence on spectral purity and stability of the oscillator is described. It is also shown how these sources can be identified and localized from the output signal characteristics.

Fluctuations due to the resonator are closely studied.

Different types of oscillators (quartz oscillator, atomic clock, etc ...) are examined, and the contribution of noise sources to the limitation of stability is discussed.

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Invited Paper

IS THE 1/f NOISE PARAMETER α A CONSTANT?

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Recent experimental studies on 1/f noise will be reviewed. The validity of the empirical relation and the value of the parameter α will be investigated. It has been demonstrated [1,2] that the conductance fluctuates

$$\frac{S_G}{G^2} = \frac{\alpha}{Nf} \tag{1}$$

In 1969 Hooge proposed this equation as an empirical relation for the 1/f noise in homogeneous metal and semiconductor samples. N is the total number charge carriers and α is a dimensionless constant of the order 10^{-3} when lattice scattering prevails. Only real 1/f spectra with the exponent between 0.9 and 1.1 will be considered here. The consequences of the validity of Hooge's empirical relation (1) for samples of a given material with different N are: (i) *Whatever the free charge carriers do, they do it independently.* (ii) *The 1/f noise in such samples is a bulk effect and not a surface effect.* Relation (1) holds for thin gold film [3] with $\alpha = 2\times10^{-3}$ and N ranging over 3 decades. Further experimental evidence for the empirical relation is given by Fleetwood et al. [4] for platinum samples with $10^7 < N < 10^{14}$ and $\alpha = 2\times10^{-4}$.

From a number of experiments it followed that the conductance fluctuations are caused by mobility fluctuations and not by number fluctuations [5]. The next questions are then: Does 1/f noise parameter α depend on the kind of scattering? Is α a universal constant for metals and semiconductors at all temperatures?

From observed α-values in Ge and GaAs samples having lattice and impurity scattering it was demonstrated that a reduced mobility yields reduced α-values [6]. The results can be expressed as

$$\alpha = \left[\frac{\mu}{\mu_{latt}}\right]^2 \alpha_{latt} \tag{2}$$

Relation (2) follows from $1/\mu = 1/\mu_{imp} + 1/\mu_{latt}$ if the 1/f noise is assumed in μ_{latt} according to (1). Here μ is the mobility of free charge carriers and μ_{latt} the mobility that would be present without impurities. α_{latt} turned out to be 2×10^{-3} at room temperature while α ranged between 10^{-6} and 2×10^{-3}. The α-value of 2×10^{-4} for platinum of Fleetwood et al. [4]

can be interpreted as $\alpha_{latt} = 3x10^{-3}$ by using their observed mobility ratio $\mu/\mu_{latt} = \frac{1}{4}$. Further evidence for eq. (2) was found by Palenskis and Shobliskas [7]. They demonstrated that the reduction in α proportional to $(\mu/\mu_{latt})^2$ is independent of the way in which the ratio μ/μ_{latt} was realized: either with the help of temperature 77K<T<400K or by changing the amount of impurities. α_{latt} in their experiments was $9x10^{-4}$ for p-type Si and $2x10^{-3}$ for n-type in the whole temperature range.

Another demonstration of lattice scattering as the only source of 1/f noise is given by noise measurements on thin bismuth films at room temperature [8]. In thin layers the mobility is reduced by grainboundary scattering and nearly in elastic surface scattering. Thin samples having a reduced mobility show reduced α-values. Bisschop and de Kuijper [9] found agreement between calculated and experimentally observed α-values for bismuth films of different thickness in the temperature range of 77K-300K.

At large electric fields the electrons are scattered mainly by optical phonons. This hot electron effect reduces the mobility and the α-values in a way similar to eq. (2) [5].

In consequence of eq. (2) α is not constant when several scattering mechnisms are present simultaneously. So in the present situation we face two problems: (i) Is α_{latt} constant at room temperature? (ii) How does α_{latt} depend on temperature? The answer to the first question is that often α_{latt} is about 10^{-3} at room-temperature. Yet there are unexplained exceptions.

Often a large scatter in α-values is observed even on nominally "identical" samples. An explanation could be that in calculating α from accurate noise measurements (20%) we always have to use several parameters. It if often doubtful if all parameters are sufficiently well known e.g. homogeneity of doping, dimensions and quality of contacts, surface layers, degree of adhesion between the film and the substrate etc. Non-homogeneous samples and noisy contacts often result in eroneous high α-values. Surface treatments and etching have a strong influence on the 1/f noise and can results in low α-values [10,11].

As to the question of temperature influence there are no unambiguous answers. We observed a strong temperature dependence of α for p-type Si of 30 Ωcm and p-type Ge of 13 Ωcm although we assume mainly lattice scattering in the whole temperature range. Decreasing α-values with decreasing temperature were also observed by Duta and Horn [12] in thin metal films. There are other examples where α is very weakly temperature dependent if at all. [5,9].

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1/f NOISE IN RESISTORS AND THIN FILMS

L1

1/f noise in cermet and metanet resistors.

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In this paper noise measurements are reported on screen printed cermet and metanet resistors of equal geometry. The cermet thick film resistors are screen printed with Dupont 1300 pastes. The metanets are made of special designed Sprague pastes, and are only a few hundred Å thick. Both pastes are of great commercial importance, and are the basis of extremely reliable thick film resistor networks. Nevertheless the electrical behaviour of these resistors is yet not well understood. This is mainly due to the non homogeneous structure of the fired resistor : conductive particles embedded in a glassy matrix. Noise measurements combined with temperature coefficient (TCR) measurements are designed to get a better insight in the electrical behaviour of the resistors.

Because metanets are extremely low noise resistors, extra care had to be taken to the noise measurement equipment, especially to the grounding and shielding. The resistor noise is amplified by a JFET amplifier. The amplified noise is sampled and the noise spectrum is digitally calculated using a fast fourier transform. For low resistor values an impedance transformer is placed in front of the amplifier and for extremely low frequencies a digital cross correlation technique is used [1]. This allowed us to measure 1/f noise in the

frequency range of 10^{-2} to 10^{4} Hz for resistors varying from $5\ \Omega$ to 10^{4} K Ω. Our noise measurements may be divided into three parts. First we examined the presence of contact noise. No significant contract noise was found. In the second place we verified the square dependence of the paste noise on the DC current. Within the measurement accuracy this relation was confirmed. In the third place we verified the 1/f behaviour of the noise spectrum of boty type of resistors. Although both pastes behaved similar, there was a remarked difference in noise level. The thin metanet resistor (400 Å) showed a low noise index (NI) of -24 db for a 60 KΩ resistor, compared to a NI of -18 db of a 15 μm thick 60 KΩ cermet resistor.

Until now no physical model is available to explain 1/f noise in screen printed resistors. As 1/f noise in thick film is believed to be a volume effect [2], we tried to link 1/f noise with the bulk transport properties. Generally it is assumed that the transport properties are determined by the amorphous layer between the conductive particles. One normally assumes a variable range hopping mechanism, leading to a TCR behaviour proportional to :

$$\mathrm{TCR} \sim T^{1/2} \exp(T_o/T)^{1/4} , \qquad (1)$$

which shows a minimum at a temperature T_{min} which is inverse proportional to the density of localised states at the Fermi level per unit energy in the amorphous layer. The TCR of the metanets as well as the TCR of the cermets agreed very well with expression (1), but the metanets showed a much smaller T_{min} (163K) than the cermets (270 K). Thus it may be concluded that most probably the current and the noise mechanism in both pastes are the same. A possible link between the noise and the current mechanism is to relate the 1/f noise to the tunnel process involved in variable

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hopping, which gives rise to a broad spectrum of time constants. A second remarkable fact is that although metanets are much thinner than cermets, metanets are less noisier than cermets. This makes metanets more attractive from the point of view of noise index.

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L1

Removal of 1/f Noise in HgCdTe by sputtering

Kangli Zheng, Kuang-Hann Duh and A. van der Ziel*

Flicker noise or 1/f noise, is usually explained in terms of a wide distribution of time constants. The theory can be formulated as follows. If a noise current $\Delta I(t)$ has a single time constant τ, then its spectrum is

$$S_{\Delta I}(f) = 4\overline{(\Delta I)^2}\ \tau/(1+\omega^2\tau^2) \tag{1}$$

Let there be a normalized distribution in τ of the form

$$g(\tau)d\tau = \frac{d\tau/\tau}{\ln(\tau_1/\tau_0)} \quad \text{for } \tau_0 < \tau < \tau_1 \tag{2}$$

$$= 0 \text{ otherwise,}$$

where normalization means that

$$\int_0^\infty g(\tau)d\tau = 1 \tag{2a}$$

Integrating over the time constant distribution yields

$$S_I(f) = (B/f)\ [\tan^{-1}(\omega\tau_1) - \tan^{-1}(\omega\tau_0)] \tag{3}$$

Where B is a constant. The high-frequency part of the spectrum may be expressed as

$$S_I(f) = [\pi B/(2f)][1-(2/\pi)\tan^{-1}(\omega\tau_0)] \tag{3a}$$

and the low-frequency part of the spectrum may be written

$$S_I(f) = (B/f)\tan^{-1}(\omega\tau_1) \tag{3b}$$

Suh and van der Ziel observed spectra of the form (3a) with a clear changeover from $1/f$ to $1/f^2$ around $\omega\tau_0=1$.

We have observed spectra of the form (3b) in $Hg_{1-x}Cd_xTe$ samples ($x = 0.25$) that were sputter-cleaned in a mercury discharge system. Before the cleaning procedure the spectra were of the form A/f throughout. Figure 1 shows the resulting after all sputtering; the best fit gave $\tau_1=2.8 \times 10^{-4}$ sec. Figure 2 gives the results of another sample with a time constant τ after sputtering that was about a factor 10 larger than Fig. 1.

We checked the ohmic contacts of the sample shown in Fig. 1 and found that they were very good. This is corroborated by the facts that the current

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*The research at Dept. of Electrical Engineering of University of Minnesota was supported by NSF.

dependence of the noise was as I^2, as expected for true resistance fluctuations, and that the noise was independent of the polarity of the current; poor ohmic contacts usually do not have an I^2dependence and the noise depends on the polarity of the current.

The sample shown in Fig. 2 was not as homogeneous as the one shown in Fig. 1 and had grain boundaries. This may explain why τ_1 is different for the two samples. The increased noise probably comes from the grain boundaries.

The time constant τ_1 of the sample of Fig. 2 decreased strongly with increasing sputtering time, whereas the same process decreased the parameter A of the A/f spectrum. This may be associated with a reduction in grain constant of the centers (parameter τ_1). When τ_1 was plotted versus the thickness of the removed layer we obtained a linear relationship, which we cannot fully interpret at present.

Apparently the sputtering cleans the centers with long time constants from the surface, so that only centers with short time constants are left.

This is the most clear-cut evidence so far that the 1/f noise in $Hg_{0.75}Cd_{0.25}Te$ is generated at the surface. Moreover, it proves the validity of McWhorter's 1/f noise model for this material.

We believe that the noise left after sputtering is of the bulk type, such as caused by bulk mobility fluctuations, because after the surface was sufficiently cleaned the noise did not change by further sputtering. After exposure to air for 35 minutes, the noise spectrum increased somewhat, presumably because the factor B in (3b) changed.

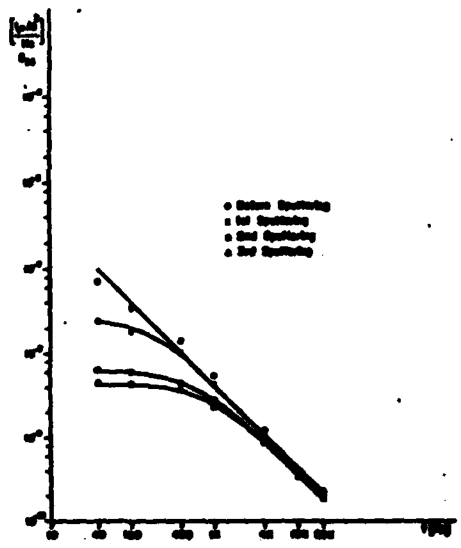

Fig. 1 Low frequency noise spectrum for $Hg_{0.75}Cd_{0.25}Te$, Device #2 at T = 297°K, P = 10^{-4} Torr, I = 2mA, measured points and theoretical curves (solid lines).

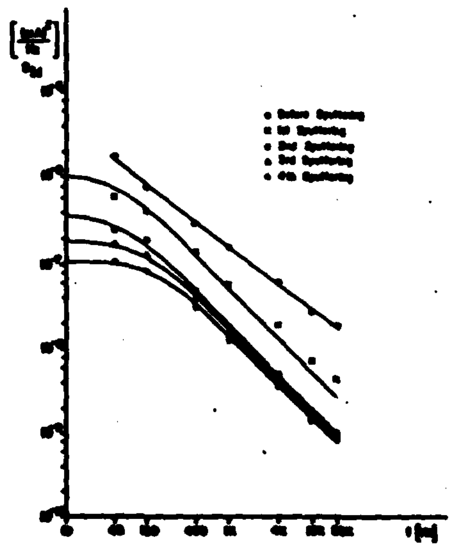

Fig. 2 Low frequency noise spectrum for $Hg_{0.75}Cd_{0.25}Te$, Device #3 (which has grain boundary) at T = 297°K, P = 10^{-4} Torr, I = 2mA, measured points and theoretical curves (solid lines).

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1/f Noise in Silicon

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We have found that in thick silicon wafers the value of the Hooge coefficient in samples with low electric fields, no detectable non-phonon scattering, and homogeneous carrier concentration is about $2\cdot10^{-6}$. In thin silicon-on-sapphire wafers (SOS) the value is about 10^{-4}. The conductivity fluctuations in SOS and thick wafers are approximately scalars. The statistics are Gaussian. At room temperature the magnitude of the Hall noise is slightly less than expected for pure number fluctuations but the cross-spectrum of the Hall noise and resistivity noise has the sign and nearly the magnitude predicted for fluctuations in the number of majority carriers. The likely model would involve fluctuating occupancy of traps, which can be shown theoretically and experimentally to give about the right ratio of mobility fluctuations to number fluctuations. At 100K the magnitude of the Hall noise fits a simple carrier number fluctuation model.

The noise spectra in SOS show small reproducible deviations from a 1/f power law. These are correlated with the temperature dependence of the noise magnitude[1] in a manner similar to that found in metal films by Dutta et al.[2] (Similar correlations are found by us in carbon resistors and may be calculated from data[3] on thick film resistors.) These correlations indicate thermally activated rate limiting steps for the noise generating processes. The absence of a strong overall temperature

dependence of the noise magnitude indicates that the thermally activated transitions are between states which differ in energy by much less than the typical activation energy (~ 0.5 eV). We have not been able to reconcile this fact with any theory in which the slow noise kinetics are those of trapping-detrapping. Our data are consistent, however, with models in which the slow processes are lattice rearrangements (e.g. impurity diffusion, transitions in two-level defect states), particularly near the surface. Such processes would affect the depths of fast traps in SOS and could couple to the conductivity by other mechanisms in metals.

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L1

EXPERIMENTAL ESTIMATION OF THE TEMPERATURE FLUCTUATION IN A CURRENT-CARRYING METAL MICROBRIDGE

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A new method is devised to estimate the temperature fluctuation in a current-carrying resistor. The experimental setup is shown in fig.1. An indium microbridge sample (S_V/V^2 at 1Hz is more than -70db) is driven with a constant current source and the voltage fluctuation across the sample is detected.

The thermal noise component (1-160kHz) is squared to produce the variance fluctuation, which contains both the resistance and temperature fluctuations.

From the value of the relative resistance fluctuation $\Delta R/R_0$, the relative variance fluctuation $\Delta P/P_0$, and their product $\Delta R \Delta P/R_0 P_0$, the relative temperature fluctuation is calculated.

$$\langle(\Delta T/T_0)^2\rangle = \langle(\Delta R/R_0)^2\rangle + \langle(\Delta P/P_0)^2\rangle - 2\langle\Delta R \Delta P\rangle/R_0 P_0.$$

The measured spectra are shown in figs.2 and 3. The temperature fluctuation is proportional to $f^{-1.1}$, while the resistance fluctuation to $f^{-1.2}$ and the variance fluctuation to $f^{-1.0}$. The temperature fluctuation in the band of 10^{-4}- 10^{-2}Hz is $0.13K^2$, which is many orders of magnitude larger than the expected value for the equilibrium temperature fluctuation in the sample used in the measurement.

The correlation coefficient between the resistance and temperature fluctuations is also obtained. In the frequency range of 10^{-4}- 10^{-2}Hz the correlation coefficient is about -0.6, which means that about 60% of the resistance fluctuation is originated from the temperature fluctuation.

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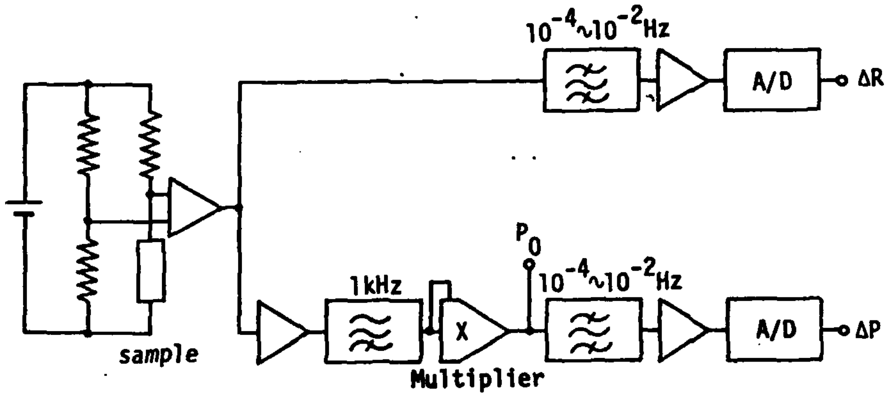

Fig.1 Measuring setup for temperature fluctuation.

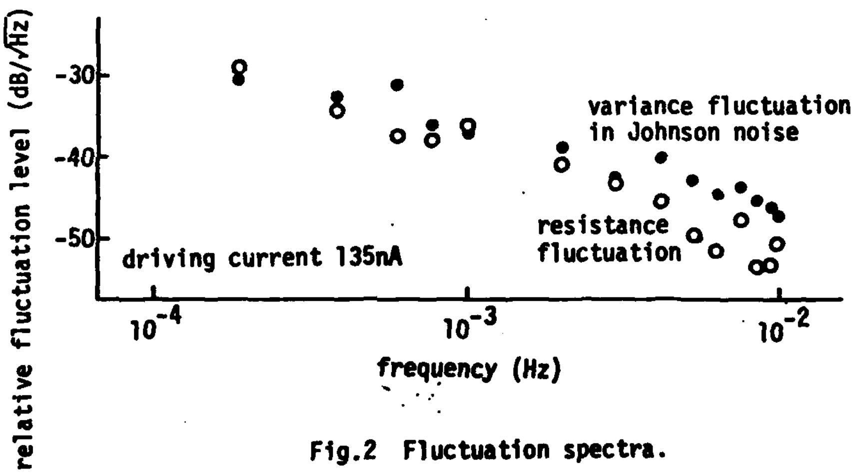

Fig.2 Fluctuation spectra.

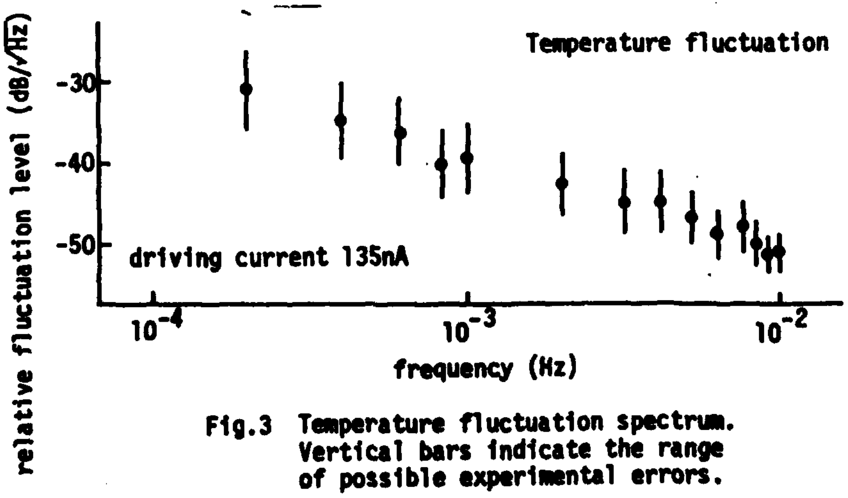

Fig.3 Temperature fluctuation spectrum.
Vertical bars indicate the range
of possible experimental errors.

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1/f Noise in metal films of submicron dimensions. J. Kilmer, G. Bosman, C.M. Van Vliet, and A. van der Ziel, Department of Electrical Engineering, University of Florida, Gainesville.

The 1/f noise of gold films, prepared by Dr. E. Wolf of Cornell University, was measured in the temperature range 10K - 300K. The Hooge parameter α_H was determined from $S_I(f)/I^2 = \alpha_H/fN$, where N is the number of valence electrons in the film. The results for α_H are shown in Fig. 1.

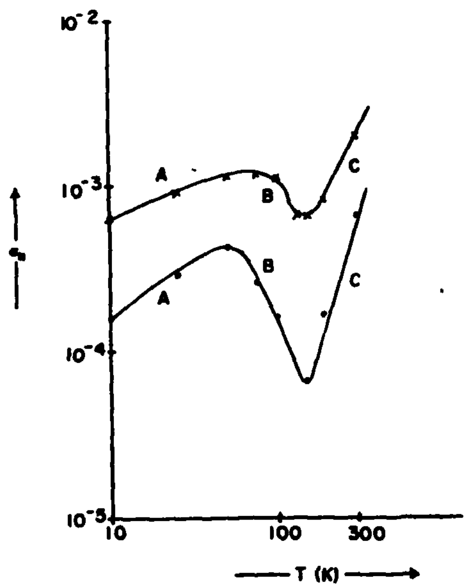

Figure 1

In the graphs there are three regions indicated. The high temperature noise (region C) is believed to be "type B" noise in the Dutta-Horn terminology[1)]; it is presumably caused by dislocations. Regions A and B are attributed to mobility-fluctuation noise. However, we believe that Hooge's formula should be modified for metals and degenerate semiconductors, since only the fraction $n = (2kT/\varepsilon_F)N$ is available for scattering fluctuations; here ε_F is the Fermi level as

measured from the conduction band bottom (a more accurate expression involves a ratio of Fermi integrals). Substituting the above into Hooge's formula gives $S_I(f)/I^2 = \alpha_{true}/fn$, with $\alpha_H = \alpha_{true}(\epsilon_F/2kT)$. In region B, α_{true} is apparently close to constant. In region A, α_{true} decreases presumably due to a freeze-out of Umklapp processes. At 10K, α_{true} is of order 10^{-7}, a value compatible with Handel's theory.

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L1

1/f Noise in the Trichalcogenides $NbSe_3$ and TaS_3

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The two quasi-one-dimensional trichalcogenides $NbSe_3$ and TaS_3 exhibit a high temperature metallic phase and a lower temperature phase in which there is a charge density wave (CDW). Below the transition temperature, T_c, $NbSe_3$ remains metallic but with fewer electrons, while TaS_3 becomes semiconducting. In each case there is a loss of electrical conductivity on going to lower temperatures due to the immobility of the CDW. We have measured the 1/f noise in each of these materials as a function of temperature near T_c. The samples are whisker-like filaments 2-3 mm in length with transverse dimensions $\sim$ 2-10 µm. Above T_c the 1/f noise is similar to that in other metallic whiskers, i.e. it follows Hooge's expression but with magnitude $\sim$100 times that for films. Below the transition the noise is even larger. The most interesting result is that, at least for a range of values of the sample current I, the noise is not proportional to I^2 as it is above the transition.

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RESISTIVITY DEPENDENCE OF 1/f NOISE IN METAL FILMS*

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The 1/f noise of a number of different types of metal films has been studied at room temperature. In Fig. 1 we show $\gamma \equiv S_V Nf/V^2$ (where S_V is the noise power spectral density, N is the number of atoms, f is the frequency, and V is the voltage[1-3]), as a function of resistivity, ρ. The noise of nominally identical samples can vary by more than a factor of ten, which is well outside the estimated experimental uncertainties for the quantities which are thought to determine the noise.[1,2] In this talk we shall describe experimental results which suggest that stresses within the film and/or between the film and its substrate may be responsible, at least in part, for these variations. We note that stress relaxation processes involve distributions of time constants/energy scales similar to those expected for processes which cause 1/f noise.[2] Returning to Fig. 1, it is seen that the minimum level of 1/f noise of a given metal is a fairly well-defined quantity. This minimum noise level exhibits a systematic resistivity dependence which cannot be accounted for by the semi-empirical formula developed by Hooge, Vandamme, and co-workers.[1,4] Rather, we find that it is well-described by the formula[3]:

$$S_{V,min} = \left(\frac{\rho_o}{\rho}\right) \frac{V^2}{Nf^{\alpha}} \quad , \tag{1}$$

where $1.0 \lesssim \alpha \lesssim 1.3$,[2,3] and $\rho_o \approx 6 \times 10^{-3}$ $\mu\Omega$-cm. A theoretical basis for (1) is not clear at this time. This problem is discussed further elsewhere.[3,5]

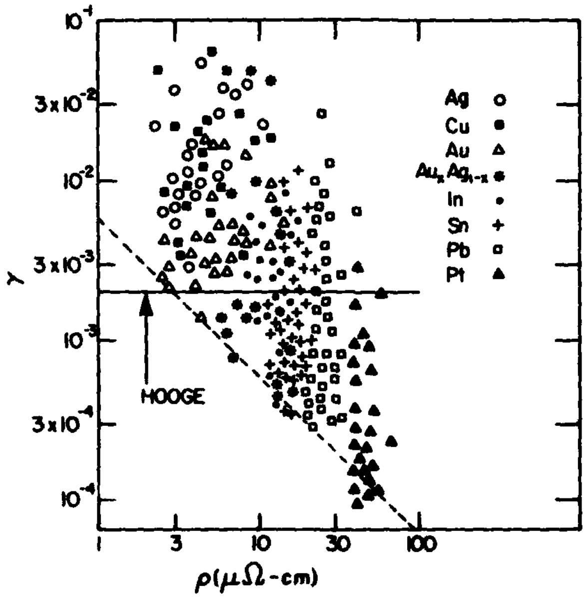

FIG. 1. $\gamma \equiv S_V N f/V^2$ at $f = 10$ Hz as a function of resistivity for several metals.[2,3] The solid line indicates the prediction of Hooge's empirical formula,[4] $\gamma = 2 \times 10^{-3}$, corresponding to the case in which electron-phonon scattering is the dominant contribution to the resistivity.[1,4] The dashed line represents (1).

*Supported in part by NSF-MRL Grant DMR80-20249, a David Ross Fellowship (D.F.), and an Alfred P. Sloan Foundation Fellowship (N.G.).

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L1

1/f NOISE IN ZnO VARISTORS

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The structure of zinc oxide varistors constitutes of a number of ZnO grains /10 - 20 μm thick/ each surrounded by thin insulating layer /30 - 100 Å/ of Bi_2O_3 based oxides. The varistors can be considered as an array of back-to-back Schottky barriers. The I-U characteristic of one such a back-to-back Schottky barrier unit in the ohmic region can be written as follows[1]

$$I_g = \frac{A_g A^* T^2}{1 + v_R/v_D} \exp(-q\phi_b/kT) \cdot \frac{qU}{gkT} , \qquad (1)$$

where v_R is the recombination velocity, v_D the so called effective diffusion velocity, A_g the cross-section area of the junction, A^* the Richardson constant, ϕ_b the barrier height, g the number of grains connected in series across the distance between the two varistor electrodes and U the voltage applied to the varistor. In Eq.(1) only v_D depends on mobility, that is $v_D \cong \mu E_m$, where E_m is the maximum value of the field in the depletion region. In our case $v_R \ll v_D$. Inserting v_D fluctuation into Eq.(1) it can be shown that the relative power spectral density of 1/f current fluctuations in the varistor is[1]

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$$\frac{S_I}{I^2} = \frac{\alpha v_R^3 R_o C_o}{4 f g A_{eff} U_D^2 N_D \mu^2}, \qquad (2)$$

where α is the Hooge parameter[2], R_o and C_o are the ohmic region resistance and capacitance of the varistor respectively, f the frequency, A_{eff} the total cross-section of the barriers in a plane parallel to the varistor electrodes, U_D the diffusion voltage and N_D the concentration of donors in the ZnO grains. The linear relation of S_I/I^2 vs R_o was confirmed by the experiments /see Fig. 1/. The straight line in Fig. 1 was drawn for $g = 22$, $N_D = 6 \cdot 10^{18}$ cm^{-3}, $U_D = 0{,}7$ V estimated all from the conduction mechanism investigation and for α assumed as equal to 10^{-5}.

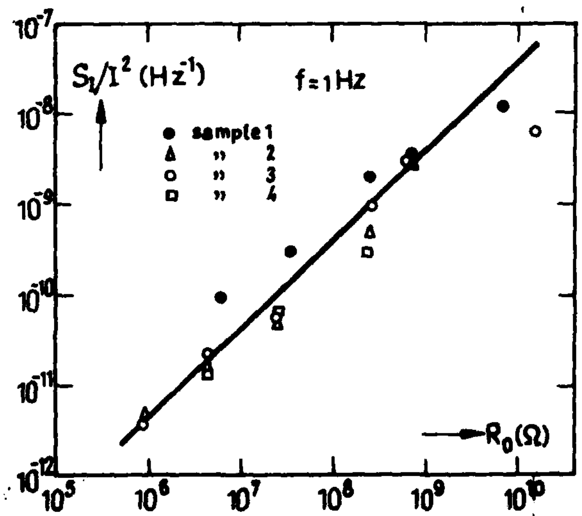

Fig. 1. 1/f noise spectral density at f = 1 Hz vs the ohmic region resistance R_o for 4 different Siemens varistors SI14K 17 ON. R_o is varied by temperature.

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THURSDAY MORNING

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OSCILLATORS

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CHAOTICS STATES AND ANORMALOUS NOISE IN RESONATORS

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Resonating systems, like many physical systems, exhibit characteristics, which are not linear any more, when driven at high level. The nonlinearities induce resonance frequency variations versus driving power (amplitude-frequency effect), distorsions of phase and amplitude responses. Coming along with those effects are bi or multistability, harmonic and sub harmonic generation, hysteresis. Finally unstable states, chaotic states, can take place.

In the present paper sub harmonic generation and chaotic states are studied in the cases of resonators with high or low Q-factors.

A large increase of noise in the system is observed, as well for white pedesta noise, as for sidebond noise. This last one show a spectrum with a frequency law clc to $1/f^2$. The statistical characteristics of these noises are analyzed, in order to de termine if they are pure random noises or rather random-like phenomena with quasi-continuous spectrum.

Modelization of such nonlinear systems is presented first. Then the results of measurements performed on real systems, quartz crystal resonators (high Q-factor) and phase lock loop (low Q-factor) are given.

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Noise Phenomena in Ringlasers

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The ringlaser is one of the most remarkable versions of oscillators at optical frequencies, where quantum-limited noise of the oscillation frequency f_0 is routinely achieved in the commercial application, the laser gyro. Over a wide range of Fourier frequencies (at least up to MHz), the quantum noise can be expressed as a white "power" spectral density $S_{\Delta f}$ of the fluctuating frequency $\Delta f(t) = \frac{1}{2\pi}\,\frac{d\phi(t)}{dt}$ with the value

$$S_{\Delta f} = 4\pi^2\ hfo^3/Q^2P = a \qquad (Hz^2/Hz) \qquad 1)$$

[Q = quality factor of (passive) laser cavity, P = power lost in cavity, h = Planck's constant.][1] Eq. 1) corresponds to an Allan variance

$$\sigma^2_{\Delta f} = a/2\tau \qquad [\tau = \text{sampling time}] \qquad 2)$$

in the time domain. Linewidths of the order of $\Delta f/f \sim 10^{-17}$ follow from eq. 1, quite surpassing practically achieved line-widths of H-masers or Mössbauer lines, to give two examples.

A classic difficulty in measuring the frequency fluctuation of highly stable oscillators is the reference oscillator, whose stability enters in the overall discussion. Early measurements of the equivalent linewidth[2] had to be done over short time intervals, to avoid broadening due to drift. In the ringlaser where the closed feedback path occupies a finite area, this problem is solved by exciting two or more counter-rotating modes in the same cavity. Thus, cavity fluctuations are compensated in first order. Furthermore, several elegant ways to bias the resonant frequencies exist: Sagnac effect[3], Fresnel drag[4],

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nonreciprocal optical phenomena.

Besides white noise, generally low frequency excess noise is observed.[5] Currently a 6 m ring is studied in our lab, and data of commercial gyros are analysed. The results can be expressed in an expansion of power spectral density vs Fourier frequency f as[6]

$$S_{\Delta f}(f) = h_0 + h_{-1} f^{-1} + h_{-2} f^{-2} + \ldots \qquad 3)$$

or equivalently as an Allan variance,

$$\sigma_{\Delta f}^2 = a_{-1} \tau^{-1} + a_0 + a_1 \tau^1 \qquad 4)$$

Of particular interest, besides $h_0 = a$, is the magnitude h_{-1} of the flicker noise in frequency. Over the past 1 1/2 decades, published data show a gradual reduction of the flicker noise coefficient h_{-1} and the random walk noise coefficient h_{-2} (similar to developments in active electronic devices). For the measurements to be presented the corner frequency of flicker noise and white noise is of the order of 10^{-3} to 10^{-4} Hz, which allows the observation of quantum-limited noise over time spans of the order of minutes to hours.

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ULTRA LOW NOISE GaAs MESFET MICROWAVE OSCILLATORS

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- : -

INTRODUCTION

Phase noise often limits the performance of today's microwave communication systems. Indeed it degrades adjacent channel sensitivity.

Therefore, the high phase noise observed in GaAs MESFET oscillators makes them of limited use. Indeed the single sideband phase noise of a dielectric resonator stabilized MESFET oscillator (FET DRO) at 10 KHz offset from the carrier is hardly lower than - 90 dBC at 12 GHz. As a comparison, commercially available Gunn diodes oscillators exhibit a phase noise better than - 100 dBC in the same conditions. Unfortunately, they have a very poor efficiency and a bad long term stability. On the other hand, GaAs FETs are now common devices universally used in most microwave systems and FET's oscillators may have up to 40 % of efficiency. Therefore, the designing of ultra low noise FET DRO's has now become a major goal.

Two ways of decreasing the phase noise in FET DROs

The high phase noise in a FET DRO is the result of the carrier phase modulated by the low frequency excess noise (LF noise) inherently present in the device. Therefore, decreasing the phase noise can be obtained either by decreasing the excess noise or the modulation sensitivity.

The low frequency excess noise was therefore extensively analysed both theoretically and experimentally. It was found that it depends mainly on the presence of traps and defects in the three major regions of the device : lateral regions including the air-semiconductor interface, depleted region and neutral region beneath the gate. From this analysis to be presented at the conference, it can be stated that the device to be selected for the oscillator must have the largest possible sizes (mainly concerning gate width). Moreover, to select the device among several transistors processed with different techniques, LF noise measurements prior to designing the oscillator, is the most efficient and the easiest way.

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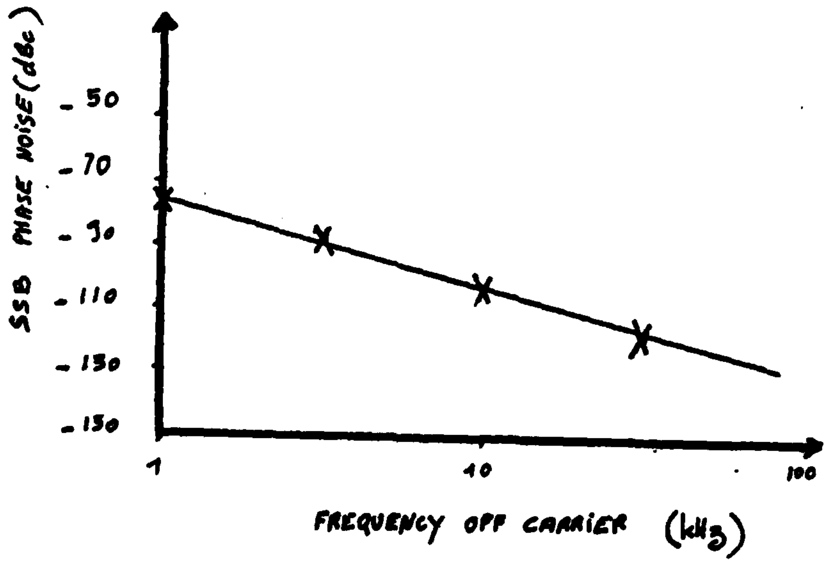
The modulation sensitivity can be decreased with an appropriate stabilization of the oscillator. Usually, a dielectric resonator is inserted in the feedback circuit. Among all the possible locations investigated for this resonator, we found that the more appropriate location for reducing the modulation sensitivity is to use the resonator as a coupling element between gate and source, drain being used as the output.

State-of-the-art noise performances

An oscillator was built with a power device previously assessed for its low frequency noise. A dielectric resonator was used as previously indicated and provides an external quality coefficient greater than 1000. The single sideband phase noise at 10 KHz offset was found to be - 104 dBC at 12 GHz. To our knowledge, it is the best noise performance so far reported for GaAs MESFET oscillators.

As a result, FET DROs can now compete successfully with bipolar or Gunn diodes oscillators and we believe that in a near future they could be, competitors with very low noise oscillators as klystrons.



Single sideband phase noise of the optimized GaAs MESFET oscillator (f = 11 GHz, P = 12 mW) -

This work was supported by the "DIRECTION AFFAIRES INDUSTRIELLES et INTERNATIONALES" of the "DIRECTION GENERALE DES TELECOMMUNICATIONS".

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Reduction of the Low Frequency Noise Sidebands in Oscillators

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Low frequency noise in an oscillator normally produces two l.f. noise sidebands around the center frequency ω_o of the oscillator. It was shown experimentally that these noise sidebands can be eliminated by using an oscillator circuit with an odd-symmetrical characteristic. A simple theory based on the van der Pol approach to oscillators can explain the observed results.

According to van der Pol[1] the time varying output current in an oscillator is represented by:

$$i = \alpha v - \beta v^2 - \gamma v^3 \tag{1}$$

where v is the applied a.c. voltage. Van der Pol omitted the term with v^2 since it did not add any new feature in the amplitude limiting action of the oscillator; we take it into account since it plays a quite important role in the purity of the spectrum of the oscillator (it increases the linewidth).

Any low-frequency noise voltage v_n, because of the term βv^2 in (1), produces noise sidebands $\omega_o \pm \omega_n$ around the oscillator frequency and so produces line broadening. In the same way an impressed low-frequency signal of frequency ω_p produces, because of the term βv^2 in (1), sidebands $\omega_o \pm \omega_p$ around the oscillator frequency ω_o. Only if $\beta = 0$, that is if the device is operating at an inflection point $(d^2i/dv^2 = 0)$, so that it provides an odd-symmetrical characteristic, will the sidebands around ω_o be missing. This property holds for any device that either has an odd-symmetrical characteristic by its own nature or in which the odd-symmetrical characteristic is provided by the circuit.

In the experiment we demonstrated two things. First that the low frequency noise in an oscillator produces two sidebands centered around the oscillator frequency ω_o and second that these noise sidebands can be reduced by achieving odd-symmetrical characteristics. This can be shown by using the oscillator of Fig. 1. After the potentiometer adjustment the injected noise (side-lobes at 210 Hz from the center frequency) and the circuit noise are clearly reduced (Fig. 2). This results in improved oscillator output purity (linewidth reduction).

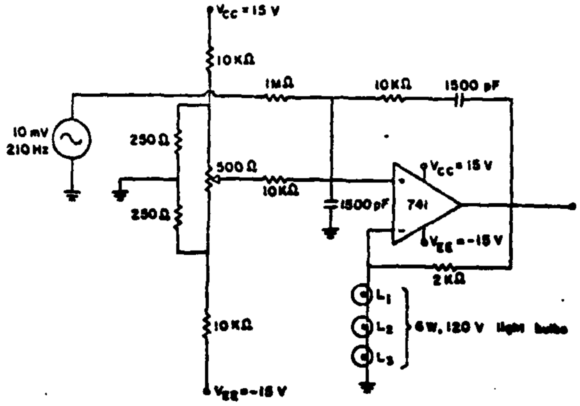

Fig. 1. Oscillator circuit using an op-amp; the 10 mV, 210 Hz signal is the impressed low frequency noise.

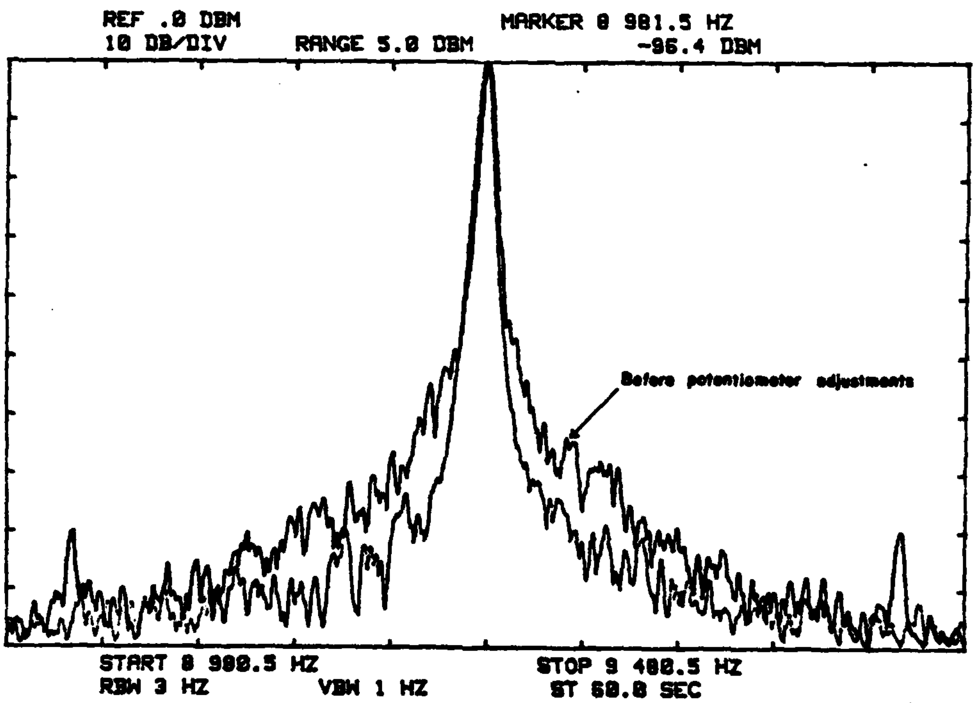

Fig. 2. Spectral intensity display of the output of the oscillator of Fig. 1 before and after the potentiometer adjustment. Injected noise and circuit noise are reduced considerably.

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Invited Paper

1/f, diffusion and thermal noise in GaAs devices

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Thermal noise in GaAs resistors is essentially velocity fluctuation noise. If Kubo's theory is applicable, the velocity fluctuations noise can be expressed as diffusion noise; if in addition the Einstein relations $qD=kT\mu$ is valid, the diffusion noise can be expressed in the Nyquist form. At the highest frequencies of operation D and μ may be frequency dependent.

Short n+-n⁻-n+ GaAs diodes, operating in the near-ballistic regime, show thermal noise, $S_I(f)=4kTg$, at moderate frequencies; here g is the differential conductance. This relationship is valid up to a forward bias up to about 0.3 Volts. Short n+-p⁻-n+ GaAs diodes have a strongly non-linear characteristic and are only near-ballistic at high forward bias (0.5 Volt); the characteristic is here due to collision limited ambipolar injection through the potential minimum at low forward bias and due to nearballistic electron injection through the potential minimum at high forward bias. The h.f. noise is thermal noise at low forward bias and thermal-like noise at moderate and high forward bias; experimentally the situation is not quite clear because of the large amount of 1/f noise present. Short p+-n⁻-p+ devices should have a characteristic with a negative conductance regime at intermediate bias; it is caused by a transition from near-ballistic ambipolar current flow at low-forward bias to collision-limited hold injection through the potential minimum at large forward bias. Permeable base transistors are in fact solid state triodes and should have near-thermal noise. Modulation-doped transistors behave as ordinary FETs and hence should have thermal noise at higher frequencies.

GaAs current limiters have one-dimensional diffusion noise consisting of a $1/f^{1/2}$ branch at lower frequencies and a $1/f^{3/2}$ branch at higher frequencies. The diffusion probably goes along dislocation lines; the diffusing particles are ions, and the activation energy of the diffusion process is voltage-dependent due to the Poole-Frenkel effect. At low temperatures the noise is 1/f noise, but some features of the voltage dependence of the $1/f^{3/2}$ noise seem to be retained.

Modulation-doped FETs have 1/f noise up to moderate frequencies; it is probably caused by interaction of electrons in the conducting channel with traps in the undoped GaAlAs layer seperating the n+-surface from the conducting channel. The low-frequency 1/f noise in n+-n⁻-n+ diodes is very small as expected for mobility fluctuation 1/f under near-ballistic conditions. The low-frequency 1/f noise in n+-p⁻-n+ devices is orders of magnitude larger and probably hangs together with the mode of current flow. It is expected that p+-n⁻-p+ devices should have relatively low 1/f noise at moderate bias. The same should be expected for permeable base transistors.

1/f NOISE IN DIODES

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BEHAVIOUR OF VARIOUS Au-InP SCHOTTKY DIODES UNDER HEAT-TREATMENT

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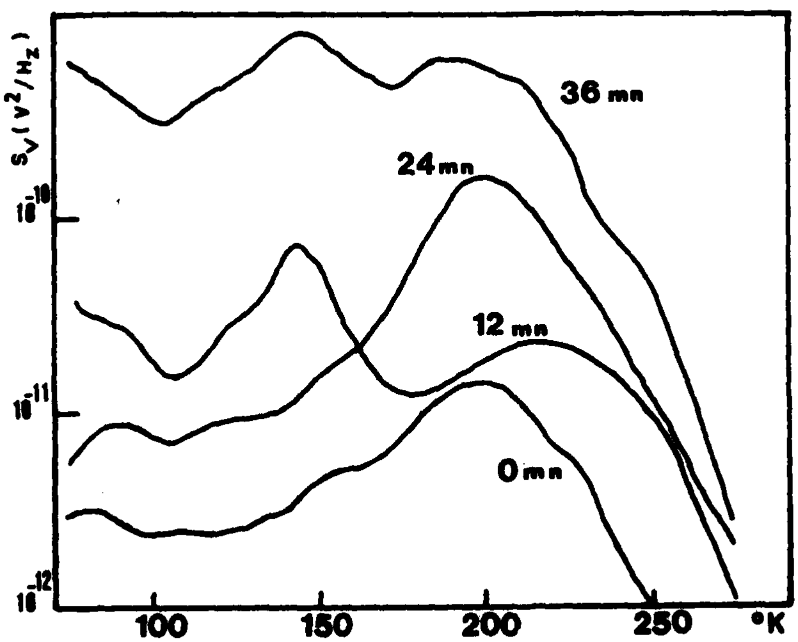
Thermal aging experiments have been made on Schottky barriers diodes. Gold contact are made on n-type bulk (100) wafers cleaned using two etching procedure. The surface are etched few seconds in $HCl-H_2O$ (5 : 100) or $Br-CH_3OH$ (3 : 100) baths giving type A or type B samples. The aim of our study is to link up the role of the interface preparation with device noise to find accurate correlations between noise and the first order parameters (from I-V and C-V characteristics). At present the relationships between the low frequency noise and the barrier quality studied in Ga As diodes are obtained with large scattered values. To prevent additonal effects of various noise factors in separate samples we have used only a sample in successive operations to alter its contact properties. The process consists in annealing treatments at temperature under 300°C.

In type A samples at room temperature the spectra contain a dominant 1/f component continuously increasing with annealing time. The noise density S_i correlate to n and ϕ_B variations with a good accuracy. The analysis of noise peak shifts with temperature yield the energy levels of various G-R centers in the depletion region. Initial measurements give a donnor level located at $E_a = E_C - E_T = 0{,}58$ ev. After a first treatment two new trap levels located at 0,44 and 0,49 ev are recorded in the spectrum. Further heat treatments give generally larger

degradation for both n,$\emptyset_B$ and noise. An unexpected behaviour of Si(Id) can be observed at specified temperatures producing negative slopes. Since it is assumed that the distribution of traps changes in the depleted region and can contain peaks in the density along the junction.

The type B samples show a very different behaviour after a similar heat treatment. Particulary the cut-off frequency of 1/f noise shows a minimum value during the heating cycles. The noise levels increase with annealing time only after 60 mn. This result is presented in relation with the n and $\emptyset_B$ variations. The measurements versus temperature give several trap levels, three of them can be fitted to these of samples A. Thus the surface preparation plays an important role in the aging behaviour with a selective effect induced by the interfacial layer on the noise performances.



Sample A noise density vs T after various heating cycles (I_d = 10μA)

Noise Properties of Bulk-Barrier Diodes

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Bulk-Barrier Diodes or Camel-diodes /1,2/ have recently gained growing interest for the application as photodiodes, mixers and as temperature sensors. This type of diode consists of a $p^{++}n^{+}p$ $(n^{++}p^{+}n)$-structure, where the thin base region forms a built-in potential barrier because it is always depleted of free carriers. The current transport is similiar to that in a Schottky-diode. Due to the different doping-levels in the emitter and collector the current-voltage characteristic is asymmetrical.

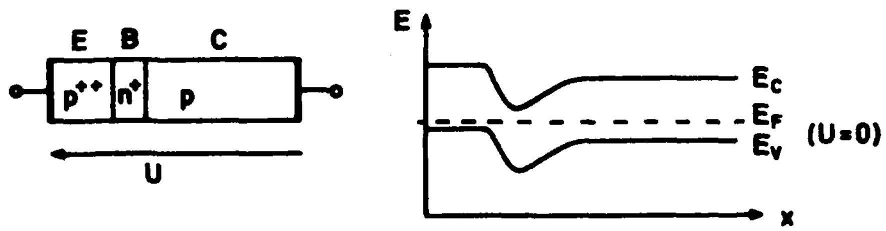

Fig.1: Structure and band-diagram of a Bulk-Barrier Diode

Mesa-diodes were prepared from ionimplanted wafers. The noise-performance of the diodes was measured with a low-noise transimpedance-amplifier and a FFT-spectrum analyzer up to 50 kHz in the current range from 0,1 μA to 100 μA in the forward and reverse direction.

The noise spectra show shot-noise in the upper frequency range. In the lower part we measured $1/f^{\delta}$-noise with δ-values from 0,6 to 0,75 depending on the magnitude of the forward or reverse current.

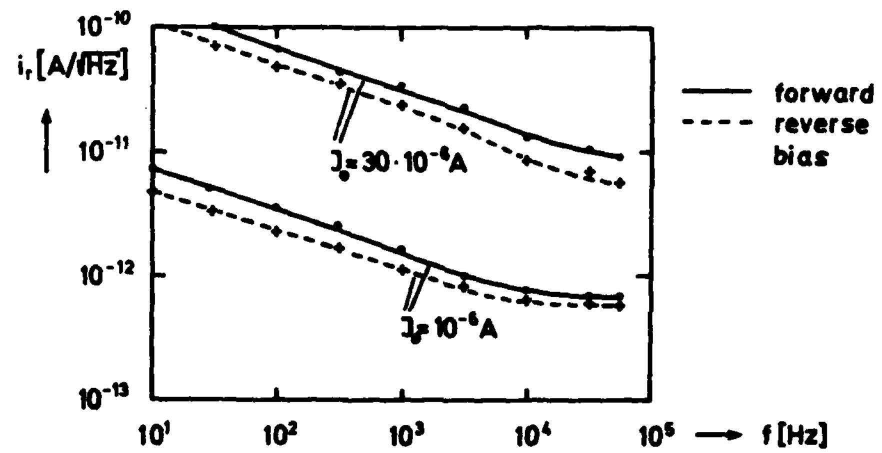

Fig.2: Typical noise spectra of a Bulk-Barrier Diode

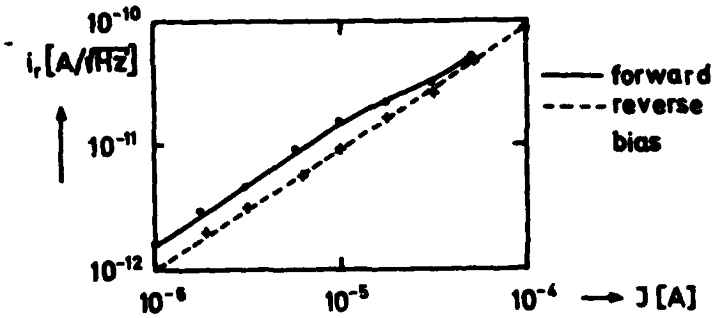

Fig.3: Current dependence of 1/f-noise at f_o = 1 kHz

In the 1/f-range the noise spectral density is proportional to I_o^2. With the same current a greater noise is measured if the diode is forward biased. By that and by a rough estimation according to Hooge's formula it can be excluded that the 1/f-noise is due to the series-resistance of the diode.

Different noise theories for Schottky-diodes were applicated to Bulk-Barrier Diodes and the results will be presented.

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/2/ H. Mader, IEEE-ED, Vol. ED 29, November 82

ON 1/f NOISE IN REVERSE-BIASED PN-JUNCTION DIODES

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During the last few years reverse-biased (HgCd)Te photodiodes have found widespread application as infrared detectors (1). Reduction of the 1/f noise level is important in systems requiring high sensitivity. Therefore an understanding of the 1/f noise in reverse-biased pn diodes is necessary. In this paper calculations and experiments of 1/f noise in such diodes will be presented.

The 1/f current noise spectral density $S_I(f)$ is calculated for two types of diodes: (i) the current is determined by diffusion in the base and (ii) the current is determined by generation-recombination in the junction. The calculations are based on the assumption that 1/f noise is due to fluctuations in the free carrier mobility (2). The results are found to be

diffusion dominated : $I = I_o\left[\exp(qV/kT)-1\right]$; $I_o = Aqn_i^2(D/\tau)^{1/2}/N_B$

$$S_I(f) = \frac{\alpha q I_o}{4f\tau}\left[\exp\left(\frac{qV}{kT}\right) - \frac{qV}{kT} - 1\right]$$

G-R dominated : $I = I_o\left[\exp(qV/2kT)-1\right]$; $I_o = Aqn_iW/\tau_j \sim (V_{bi}-V)^{1/2}$

$$S_I(f) = \frac{2\alpha q I_o}{3f\tau_j}\left[\exp\left(\frac{qV}{2kT}\right) - 1\right]^2 \exp\left(\frac{-qV}{2kT}\right)$$

Here, α is an empirical constant in the range of 10^{-4}-10^{-3} for Si, f the frequency, τ the minority carrier lifetime in the base, τ_j the carrier lifetime in the junction, A the cross-section, W the depletion layer width, n_i the intrinsic concentration, N_B the dope concentration in the base, D the diffusion coefficient minority carriers in the base, and V_{bi} the build-in potential.

Measurements were performed on silicon p^+-n diodes with A = $2.5\times10^{-7}m^2$ at 426 K. The results plotted in the figures as circles agree with the calculated results for g-r current dominated diodes (broken lines). The experimental 1/f noise curve fits the calculated one by taking $\alpha \approx 10^{-4}$ (here W ≈ 0.3 μm, τ_j ≈ 30 ns).

Tobin et al. (3) have experimentally investigated 1/f noise in (HgCd)Te photodiodes. In the figures we have plotted their results for a diffusion current dominated diode as dots. (See also fig. 5 in (3), where normalised data are given). Calculated results are given by solid lines.

Conclusions

- The 1/f noise in reverse-biased pn junction diodes can be interpreted in terms of mobility fluctuations.
- The 1/f noise level at fixed reverse bias depends on saturation current and lifetime. Low 1/f noise diodes should have low saturation currents and high lifetimes. At fixed reverse bias the shot noise is proportional to the saturation current. Consequently, the ratio of 1/f noise and shot noise depends on the lifetime only; it decreases with increasing lifetime.

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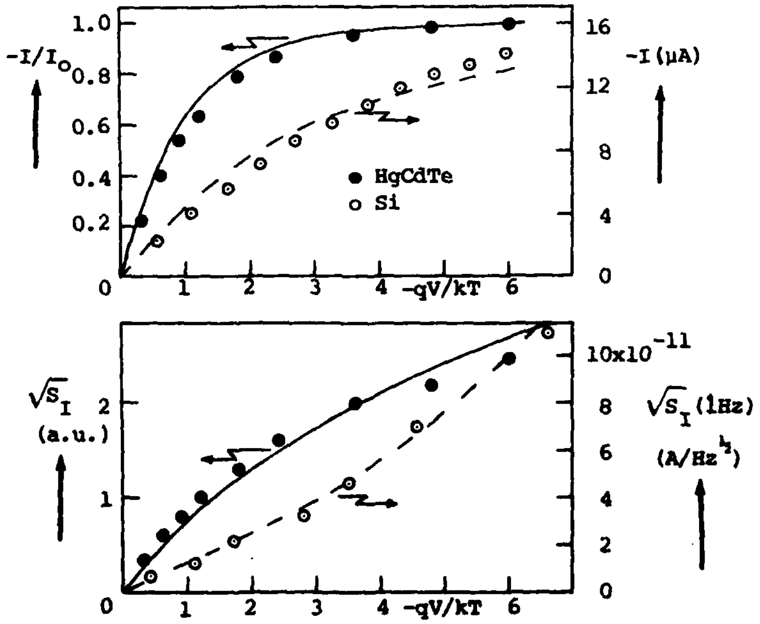

L1

"Diffusion and Flicker Noise in GaAs Current Limiters"

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A one-dimensional diffusion noise is reported in GaAs current limiters. The current limiters are ungated MESFETs with the drain source spacing L of about 1 μm. The devices are fabricated by ion implantation of Si in a semi-insulating substrate. The I-V characteristics show saturation at the bias voltage of about 1.3V. The current noise spectra of a current limiter are shown in Fig. 1. The $f^{-1/2}$ turning over to $f^{-3/2}$ spectra indicate diffusion noise. According to A. van Vliet[1] the turnover frequency f_t is given

$$f_t = \frac{D}{\pi L^2}$$

The diffusion constant D can be calculated as $3 \times 10^{-5}\,cm^2/sec$ which indicates the diffusion of ions along dislocation lines[2]. However, the details of the ion diffusion are not clear yet. The Pool-Frenkel effect modifies the diffusion constant at high electric field

$$D = D_o \exp\left[\left(-E_{ao} - \left(\frac{qV}{\pi\varepsilon L}\right)^{1/2}\right)/kT\right]$$

where E is dielectric constant, q is electron charge, k is Boltzman constant. Assuming that the ions cause the number and mobility fluctuation the $f^{-1/2}$ branch of spectrum is

$$S_I = \frac{2^{1/2}\overline{\Delta N^2}L}{\omega^{1/2}}\left(\frac{q\mu V}{L^2}\right)^2\left(\frac{N_e\mu}{N\mu_i} - 1\right)^2 \exp\frac{E_{ao}}{2kT}\exp\left[-\frac{q}{2kT}\left(\frac{qV}{\pi\varepsilon L}\right)^{1/2}\right]$$

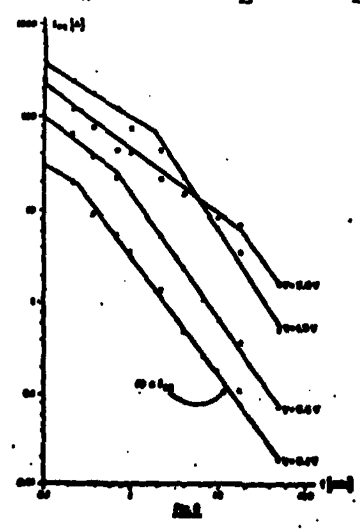

Fig. 1. Current Noise Spectra at 300°K

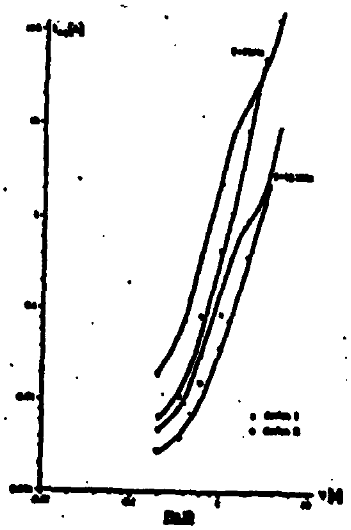

Fig. 2. Noise vs. Bias Volt at 77°K

* This research was supported by Army Research Office.

and the $f^{-3/2}$ branch becomes

$$S_I(f) = \frac{2^{3/2}\overline{\Delta N^2}}{\omega^{3/2}L}\left(\frac{q\mu V}{L^2}\right)^2\left(\frac{N_e\mu}{N\mu_i} - 1\right)^2 \exp\left(-\frac{E_{ao}}{2kT}\right)\exp\left(\frac{q}{2kT}\right)\left[\left(\frac{q}{\pi\varepsilon L}\right)\right]^{1/2}$$

where N is number of ions, N_e denotes number of electrons, ω is angular frequency. The voltage V and temperature T dependence given by these equations are in a good agreement with the experimental data. The turn-over frequency and noise spectrum density variation with temperature yield the value of $E_{ao} = 0.3 \pm 0.1$ eV which is close to the activation energy related to a leakage current in similar structures[3]. The voltage dependence of the turn-over frequency and the noise spectrum gives a somewhat higher correction to the activation energy than predicted by Poole-Frenkel effect. This can be partially attributed to a non-uniform field distribution. The non-uniform field distribution and high field effect, e.g., transfer of electrons to satellite valleys are probably responsible for decrease and saturation of noise at high bias voltage. Although this is the first detailed report on diffusion noise in semiconductor devices the $f^{-1/2}$ and $f^{-3/2}$ noise spectra have been found in some other GaAs MESFET structures.

At lower temperatures the ratio of total mobility μ to the mobility limited by ionized impurity scattering μ_i increases. That means that mobility fluctuation cancels the number fluctuation and the diffusion noise decreases. At 77°K a new noise mechanism appears. It is flicker noise which increases as V^4 (Fig. 2.). An independent experiment showed that the ohmic contacts deteriorate in current limiters below 100°K. This indicates that the flicker noise caused by contact increases very fast with the bias voltage.

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L1

1/f NOISE IN SCHOTTKY DIODES

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The noise of the Schottky diodes has recently been dealt with by Hsu and Kleinpenning. In our last paper we supposed in contrary to the mentioned papers that the noise source is localized in a volume which is substantially smaller than that of the metal-semiconductor junction. In the present paper we suppose that the diode current has two components, of which only one is the source of the noise. In parallel to this source the junction dynamic resistance and the load resistor are connected. A typical dependence of the noise voltage spectral density S_{UL} on the GaAs Schottky diode forward voltage U_F measured across the load resistor is in Fig.1.

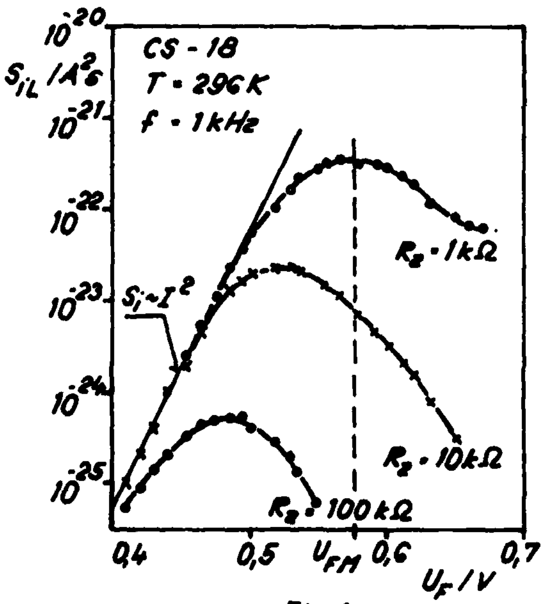

Fig.1

It is seen that at a diode voltage U_{FM} the $S_i(U_F)$ plot has a maximum for which the condition of power match does not generally apply. At low diode voltage, $U_F < U_{FM}$, the spectral density S_{iL} grows proportionally to the square of the forward current. Although the U-I curve is exponential within the entire region of the forward voltages, the ideality factor being equal to 1,05 (the diode series resistance is 7 ohms), the S_{iL} (U_F) plot shows a region where increasing the forward voltage makes S_{iL} decrease.

We attribute this effect to the existence of defects in the M-S structure. In some cases we even found out the burst noise.

In the paper we give the results of the noise vs. temperature measurements which are in good agreement with the proposed model. From the equivalent circuit it is also possible to calculate electrical parameters of the defect.

L1

1/f NOISE USED AS A RELIABILITY TEST FOR DIODE LASERS

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From Kleinpenning's [1] calculations and experiments on various types of diodes we know that for $qV > nkT$ the 1/f noise in pin-diodes obeys $S_V \propto (nkT)^2/q\tau If$, where n is the ideality factor and τ the lifetime of carriers in the i-region. At large currents I the 1/f noise may be dominated by a contact contribution and then results in $S_V \propto I^2R_c^{\,2}/f$ where R_c is the contact resistance. A relation between the 1/f noise and the diode laser lifetime can be expected. If the noise is dominated by the optical active i-region, its intensity is inversely proportional to the recombination time τ in that region. A shorter carrier life time can be due to a non-radiative parallel recombination process, resulting in larger power dissipation to maintain the same optical output. Higher temperatures reduce the device lifetime. If the noise is dominated by poor contacts, S_V is proportional to $R_C^{\,2}$. Again this defect goes hand in hand with larger power dissipation, and consequently higher device temperatures, reduced device lifetime and larger 1/f noise. A similar reasoning was held for the application of 1/f noise as a diagnostic tool for solar cells [2].

Here we report on experimental results of 1/f noise before and after accelerated life test on AlGaAs lasers and on the correlation between life test and 1/f noise. The double-heterostructure injection lasers used in this investigation are Philips type CQL 10A [3]. Accelerated life testing on the unencapsulated lasers was performed in dry air at 60°C heat sink temperature at a CW optical output of 5 mW per facet during different operating times ranging from 5 hours to 165 hours. The noise voltage measurements of the lasers were carried out at room temperature at a forward current of 1 mA, and in the frequency range of 1 Hz to 1 KHz.

The criteria from accelerated life tests to qualify a laser diode as accepted or rejected are the following. (i) The degradation

parameter which is defined by the relative increase in the driving current necessary to maintain an optical output of 5 mW and reduced to a standard time of 10^3 hours. (ii) The threshold current after life test. (iii) The laser efficiency. (iv) The current voltage characteristic and its changes after the life test. The second type of criteria donot use accelerated life tests to qualify a laser diode. They are (i) The observed 1/f noise (ii) An optical criterion which is the laser efficiency devided by the threshold current.

The experimental results obtained on 60 laser diodes of the same type can be summarized as follows: (i) The set of lasers rejected on accelerated life test criteria coincides with the set of lasers rejected on the noise criterion together with the optical criterion from a measurement after the accelerated life test. (ii) The set of lasers rejected on the second type of criteria obtained from measurements before an accelerated life test coincide with the set rejected on the first type of criteria after an accelerated life test of 165 hours. (iii) The average 1/f noise of the accepted diodes after life test as a function of life test time shows a minimum for a operating time of about 10 h. (iv) Only one diode laser out of 60 was rejected due to a poor contact resulting in $S_V \propto I^2$.

Conclusion: The observed 1/f noise shows a strong correlation with the outcome of the relialibility test for the electrical properties of the diode laser.

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L1

NOISE IN Ge AVALANCHE PHOTODIODE AT $\lambda = 1,3\ \mu m$

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The purpose of this paper is the characterization of Ge avalanche photodiode at $\lambda = 1.3\ \mu m$ The devices are manufactured by C.I.T. *Alcatel*. The photodetectors are C.G. 4000, 4100 and 4200.

They are illuminated at $\lambda = 1.3\ \mu m$ by GaInAsP/InP light emitting diode DE 1000 of the same manufacturer. We give the curves I versus V under obscurity and illumination conditions and also the capacity versus applied voltage V. The curve of noise $S_i(f)$ at obscurity showns 3 zones:

. AB : the shot noise;

. BC : burst and 1/f noise;

. CD : multiplication noise.

The presence in BC zone of burst and 1/f noise is due to a small inhomogeneity in the multiplication region which is showed by optical cartography of active surface at V = -26.4 volts. The law of multiplication noise in CD zone is given by:

$$S_i(f) = 2\ q\ I_{inj\ obs}\ M^x$$

where $x \simeq 3$ because in germanium the ionization coefficient β of holes is about 2α the ionization coefficient of electrons. The non multiplicated photocurrent at $\lambda = 1.3\ \mu m$ is the same order of value of the current at obscurity ($I_{obs} = 0.7 \times 10^{-6}$ A and $I_{pho} = 0.6 \times 10^{-6}$ A at V = -0.1 volt).

If in a first approximation we consider there is no correlation between the carriers, the noise when the device is illuminated is

the sum of two components: the noise at obscurity and the noise of photocurrent. Also the noise curve is given by law:

$$S_i(f) = 2\left[q\ I_{inj\ obs} + I_{inj\ pho}\right] M^x$$

We calculate the Noise Equivalent Power (N.E.P.) in taking account the contribution of noise at obscurity. So the relation of N.E.P. is given by:

$$N.E.P. = \frac{1}{\Gamma}\left[\frac{4\ k\ T_e}{R_e} + 2\ q\ (I_{inj\ obs} + I_{inj\ pho})\ M^x\right]^{1/2}$$

R_e is load resistance; k Boltzmann constant; T_e noise equivalent temperature at input of the amplifier.

We calculate with this relation the optimum multiplication coefficient M_{opt}. This parameter can reach with those devices a value of only 6. The relation for M_{opt} with $I_{obs} = I_{pho}$ and $x = 3$ is:

$$M_{opt} = \left(\frac{2\ k\ T_e}{R_e\ q\ I_{obs}}\right)^{1/3}$$

The main result of this work is that Germanium is not good enought ($\beta = 2\alpha$; value of energy gap too small) for avalanche photodetector at $\lambda = 1.3\ \mu m$. It is possible with Hg CdTe avalanche *photodiode to obtain* $x = 2.4$ and M_{opt} between 20 and 30. We now are studing two Hg CdTe P.I.N. photodetectors.

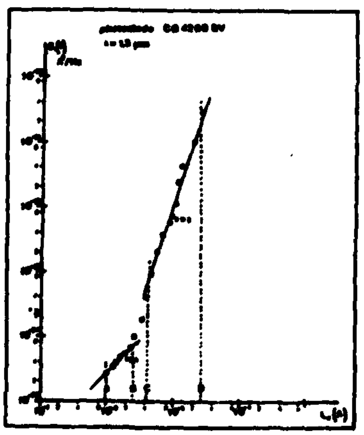

Fig. 4 – [illegible]

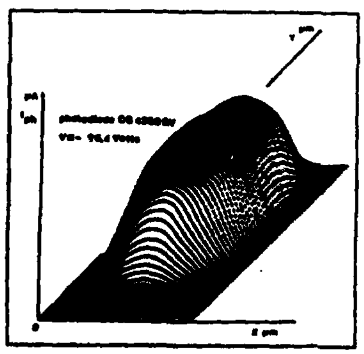

Fig. 5 — Active surface cartography at [illegible]

L1

Low Frequency Noise in InGaAs/InP-Photodiodes

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InGaAs(P)/InP-photodetectors for long wavelength optical fibre communication /1/ involve a heterojunction necessarily, since the ternary (quaternary) material has to be grown on InP substrates. With low frequency noise measurements (f<1MHz) we demonstrate that this heterojunction influences the noise behaviour in photodiodes, even if the heterojunction is located outside the depletion layer. As an example, for InGaAs/InP diodes with the pn-junction located within the InGaAs layer, the following results are obtained:

For low reverse bias, where the depletion region has not yet reached the heterojunction (homodiode operation), the spectral noise power density (SND) of the dark current is much smaller than the expected shot noise value, as seen in fig.1,region a. With increasing bias, the boundary of the depletion region crosses the heterojunction interface (arrow in fig.1) and a strong 1/f-noise sets in (fig.1,region b). The SND is proportional to the square of the excess dark current.

With illumination, this 1/f-noise is quenched, if the light is absorbed in the InGaAs layer (wavelength λ>.94μm, see fig.2), whereas it is strongly enhanced, if absorption occurs in the InP close to the heterojunction (λ=.94μm, fig.2).

L1

These noise effects are related to the InGaAs/InP heterojunction. They are discussed in terms of space charge effects and interface states at the heterojunction, the latter acting as 1/f-noise sources in analogy to observations at Schottky devices /2,3/.

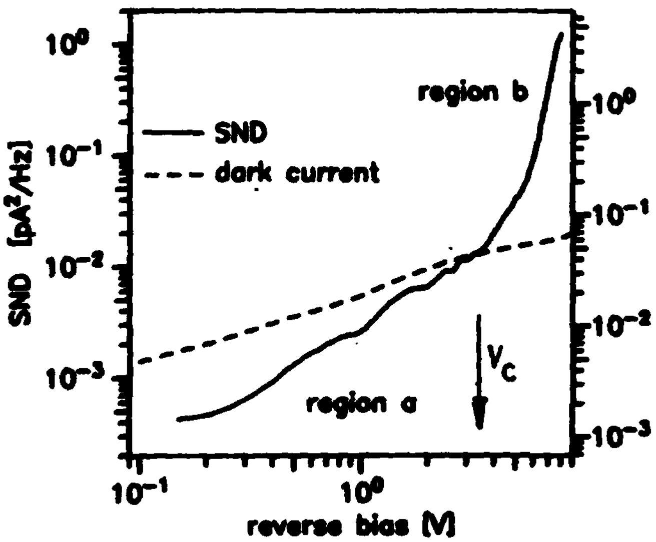

fig.1: SND of a InGaAs/InP diode vs. reverse bias, measured at 3 kHz. At V_C, the boundary of the depletion region crosses the interface. dashed: expected shot noise value of the dark current.

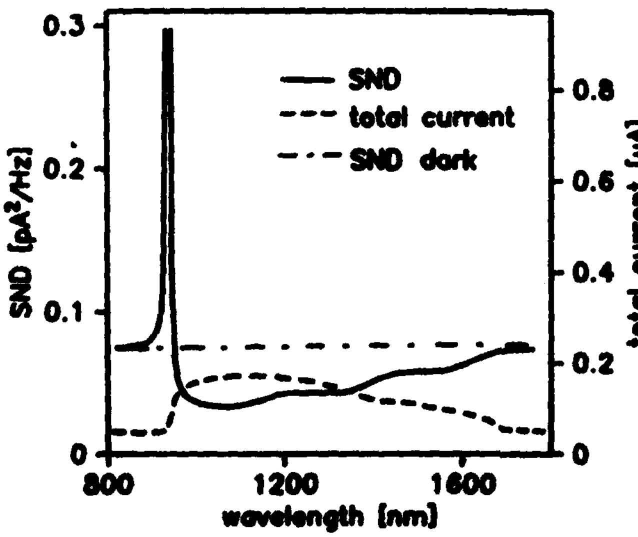

fig.2: SND of the total current with and without illumination vs. wavelength of incident light; reverse bias: 6V frequency: 3 kHz dashed: expected shot noise value of the total current.

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ON CURRENT NOISE LIMITED DETECTIVITY D^* IN PHOTOVOLTAIC (PV) AND IN PHOTOCONDUCTIVE (PC) DETECTORS

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The detectivity of photodetectors is limited by three types of noise: (i) current noise in the detector, (ii) noise due to background photons (photon noise), and (iii) noise in the electronic system following the detector. The detectivity is defined as $D^*(\lambda,f) = \sqrt{A\Delta f}/\mathrm{NEP}$, where A is the detector area, NEP the noise equivalent power, λ the wavelength, f the frequency, and Δf the bandwidth.

In this paper we present calculations for current noise limited D^* in PV and PC detectors. For a reverse-biased PV detector ($V < 0$) where the dark current is dominated by diffusion, the detectivity at peak wavelength λ_c is found to be

$$D^*(\lambda_c,f) = \frac{\eta\lambda_c}{hc}\left(\frac{N_B}{2N_cN_v}\right)^{\frac{1}{2}}\left(\frac{\tau}{D}\right)^{\frac{1}{2}}\exp\left(\frac{hc}{2kT_D\lambda_c}\right)\left[\exp\left(\frac{qV}{kT}\right)+1\right]^{-\frac{1}{2}}\left(1+\frac{f_c}{f}\right)^{-\frac{1}{2}}$$

where $\lambda_c = hc/E_g$, E_g the bandgap, η the efficiency, N_B the base dope, N_c and N_v the densities of states, τ and D the minority carrier lifetime and diffusivity in the base, T_D the detector temperature, $f_c = \alpha q|V|/8\tau kT$ the frequency where the 1/f noise equals the shot noise, and α the Hooge 1/f noise parameter ($\sim 10^{-3}$). Fig. 1a shows $D^*(\lambda_c)$ at V=0 for various T_D. The curves are calculated for typical parameters $\eta = 1$, $m_e^* = m_h^* = m_o$, $N_B = 10^{15}\,\mathrm{cm}^{-3}$, and $\sqrt{D/\tau} = 1500$ cm/s. The detectivities of some detectors are also shown. The photon noise limit is reached at $T_D \leq 250/\sqrt{\lambda_c}$ (K), with λ_c in µm.

For intrinsic PC detectors at low frequencies D^* is calculated as

$$D^*(\lambda_c,f) = (\eta\lambda_c/2hc)(\tau q\mu R_\square)^{\frac{1}{2}}(1 + f_c/f)^{-\frac{1}{2}}$$

where τ is the lifetime of excited carriers, μ their mobility, $R_\square$ the dark sheet resistance, and $f_c = \alpha/4\tau$. In fig. 1b $D^*(\lambda_c)$ is shown for $f > f_c$ and for various T_D. The curves are calculated for $\eta = 1$, $\tau = 1$ µs, $R_\square$ at maximum attainable values (i.e. $R_\square = 1/q\mu n_i t$ with n_i the intrinsic concentration), and thickness t = 10 µm. Note that for optimum performance the temperature T_D has to decrease with increasing wavelength λ_c. The frequency f_c is often found to be in the range of

10^2-10^3 Hz which is to be expected, since $\alpha \sim 10^{-3}$ and mostly $\tau \sim 1\mu s$.

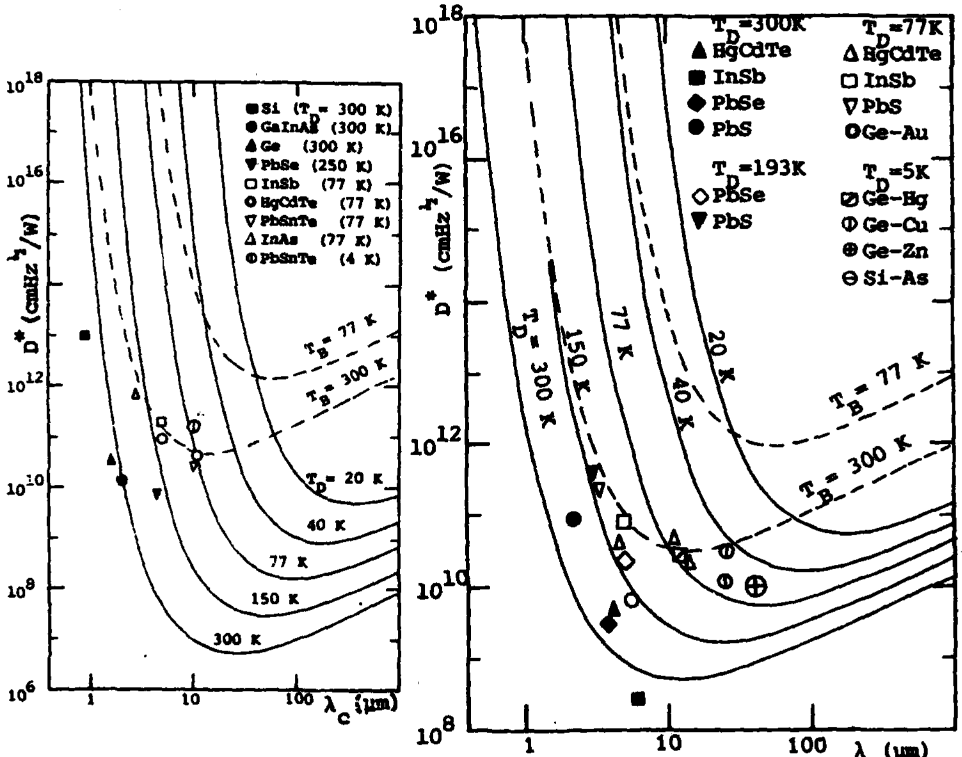

Fig. 1a Fig. 1b

Noise limited $D^*(\lambda_c)$ of a PV detector (1a) and of a PC detector (1b). Broken lines: photon noise limited D^* for two background temperatures T_B = 77 K and 300 K and for free optical view 2π sr. Solid lines: shot noise limited D^* for unbiased PV detectors (1a) and current noise limited D^* for PC detectors (1b) at various T_D.

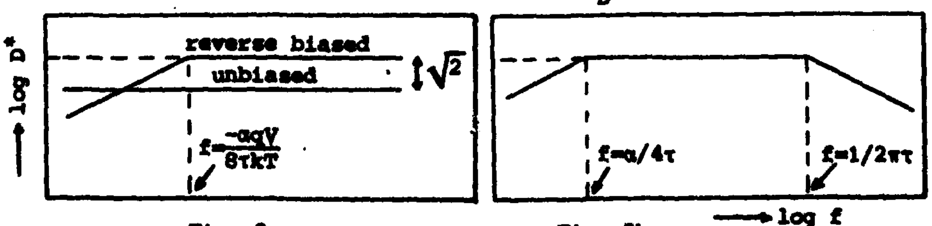

Fig. 2a Fig. 2b

Frequency dependence of D^* for a PV detector (2a) and for a PC detector (2b).

FRIDAY MORNING

ROOM B

C1

NOISE IN OTHER PHYSICAL SYSTEMS

A CURRENT NOISE INVESTIGATION ON STRESS RELAXATION MECHANISMS IN THIN METAL FILMS.

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A current noise arising from lattice defect kinetics has been recently put in evidence in continuous metal films. In particular, a noise contribution from vacancies in thermal equilibrium /1/ and from dislocations during plastic straining /2/ has been recognized.

Since any conceivable mechanism of plastic flow in crystalline materials necessarily involves the motion of lattice defects, one can reasonably look for an application of the current noise technique to the general study of the mechanical properties of metal films on substrates and, in particular, of the specific defect mechanisms leading to stress relaxation. The case of an aluminum film deposited on an oxidized silicon substrate is presented in this communication. The basic mechanisms operating in the relaxation of the stress built-up through a temperature change, via the metal-substrate thermal expansion mismatch, are investigated. Information is gathered by investigating the noise power P upon different experimental conditions:

- P measured vs. temperature at a constant strain rate. In this case a dramatic increase of the noise intensity above about 200°C is observed. Two relaxation mechanisms are correspondingly identified: a low temperature one, characterized by the motion of the dislocation lines in their glide plane, and a high temperature one, where strongly correlated rearrangements of the dislocation structure take place, presumably controlled by vacancy assisted dislocation climb.
- P measured vs. strain rate in a given temperature interval. This permits one, on the basis of the non linear dependence of P on strain

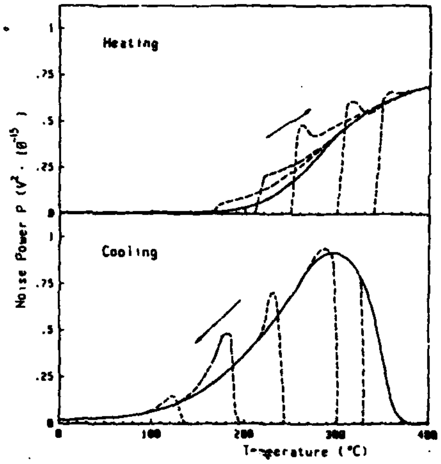

Fig. 1- Effect on the noise power of dislocation unlocking from impurities. Continuous line: noise behavior upon continuous straining. Dashed lines: straining is stopped at a given temperature and restarted when saturation of locking atmospheres around dislocations has occurred.

rate , to quantitatively evaluate the contribution of purely diffusive (i.e. involving vacancies only) creep processes.

- P measured upon material annealing. This experiment shows that in general the interaction of dislocations with foreign atoms plays a comparatively minor role in stress relaxation. Only when the deformation is stopped at a given temperature for a sufficiently long time, dislocation locking by solute atmospheres can take place. On restarting the deformation, a characteristic noise overshoot is then observed, corresponding to the unlocking of the dislocation lines.(fig. 1). Through this experiment information on the impurity-dislocation mechanism of interaction is provided.

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AD-A144 386 ABSTRACTS ON THE INTERNATIONAL CONFERENCE ON NOISE IN PHYSICAL SYSTEMS (7..(U) MONTPELLIER-2 UNIV (FRANCE)* 20 MAY 83 3/3

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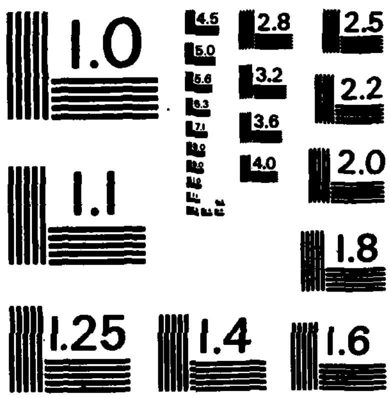

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Vacancy Noise in Metals

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Fluctuations in the number of vacancies in thermal equilibrium in metals at high temperature lead to resistivity fluctuations /1/. This "vacancy noise" contains information about the average number $\bar{N}$ and lifetimes τ of the vacancies. An advantage of vacancy noise measurements over other techniques is that they permit the determination, from a single type of thermal equilibrium measurement, of both the formation enthalpy H_V^F and the migration enthalpy H_V^M of the vacancies.

The power spectrum of the vacancy noise can be derived via a series of statistically independent pulses for any sample geometry. Vacancy diffusion to homogeneously distributed sinks and to the surface of a plate or a sphere are treated as examples. The general form of the spectrum and its dependence on the temperature and on the formation and migration enthalpies is shown in Fig.1. The slope of the high-frequency spectrum depends on the vacancy sink geometry (e.g. f^{-2} for homogeneously distributed sinks, $f^{-3/2}$ for vacancy diffusion to a surface).

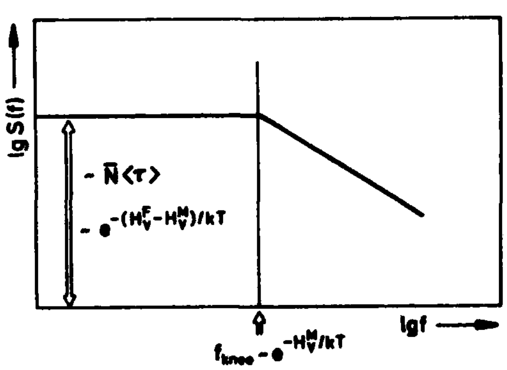

Fig. 1: Dependence of vacancy noise on temperature

In order to assess the possibility of measuring vacancy noise we calculated the power spectrum of vacancies diffusing to the surface of a typical 1.5 μm thick gold film at 1123 K (Fig. 2). The vacancy noise

spectrum is about 6 % of the Johnson noise of the specimen. Therefore the Johnson noise must be substracted by means of a second measurement without current passing through the sample. The statistical error of that difference obtained from two runs of 3600s each is also given in Fig. 2. It is shown that, with a current density of $j = 5 \cdot 10^9$ A/m^2, a vacancy noise 6 times higher than the statistical error of the measurement can be expected.

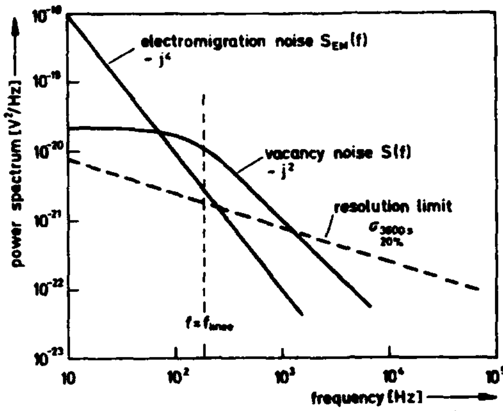

Fig. 2: Calculated power spectrum of a typical gold thin film

The practicability of measuring vacancy noise has been already demonstrated in experiments on polycristalline alluminium /1/ and gold films /2/. Although vacancy noise increases proportionally to the square of the electrical current density j, the applicable current density is limited by the j^4 dependence of an additional noise component (Fig. 2) which may be explained by resistivity fluctuations due to electromigration in the sample. As electromigration is considerably reduced in monocrystalline thin films, we suggest that in these films improved vacancy noise measurements will be attained.

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Contact Noise in Superionic Ceramics

by
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Voltage fluctuations at electrodes to polycrystalline beta alumina superionic conductors have been observed in the frequency range 1-1,000 Hz. Noise voltages exist in the absence of dc current for both two- and four-terminal samples. In addition, both the transverse and longitudinal current-dependent noise power are proportional to the square of the dc current.

Sodium β´´ alumina samples 1 cm x 0.5 cm x 0.2 cm shaped to provide either transverse or longitudinal potential electrodes use current contacts consisting of a sodium nitrate-sodium nitrite eutectic mixture. Sodium β´ polycrystalline specimens less regularly shaped are examined in the transverse 4-probe electrode configuration only. Samples are baked for several hours above 800^{0} C to eliminate adsorbed moisture, and all noise measurements are carried out in the temperature range 250^{0} C to 300^{0} C where the current contacts are molten. Three potential probe electrode materials have been examined: sodium eutectic, silver paste, and platinum foil pressed against the sample surface.

The eutectic current contacts exhibit a non-linear current-voltage characteristic which suggests a large dc resistance at zero applied voltage compared to the sample resistance of 4 ohms. At temperatures above the melting point of the eutectic mixture, dc currents can be maintained for extended periods with no indication of polarization effects. The dc voltage at the potential probes is a linear function of current through the current electrodes and the conductivity calculated from the observed resistance and sample dimensions (5 ohm-cm) agrees with published values for sodium β´´ alumina

Noise voltages are observed with a PAR 113 ac-coupled preamplifier, a tunable electronic filter and an ac voltmeter. The system accurately measures the Nyquist noise of known resistors placed at the sample position. Initial measurements have been confined to the frequency range 1 Hz to 1,000 Hz by thermal instability at low frequencies and amplifier noise at high frequencies. Current is supplied to the samples through a noiseless 100,000 ohm series resistor to reduce current fluctuations.

Noise voltages observed in the absence of current are many orders of magnitude in excess of Nyquist noise of the bulk sample and are dependent upon the electrode material at the potential probes. The sodium eutectic mixture exhibits the lowest, and the silver paste electrodes exhibit the highest noise levels. The spectral noise density in all cases varies as f^{-3}. The additional noise accompanying the presence of dc current in the specimen shows the same frequency dependence.

The observed spectral shape can be accounted for by a simple model in which a distributed contact resistance is shunted by a distributed contact capacitance. This implies that the contacts exhibit 1/f noise, which is not unexpected in view of the polycrystalline nature of these specimens. The conductivity fluctuations indicated by the current dependent noise indicates that a similar model may apply to the bulk phenomenon as well. Alternatively, noise may arise from reaction processes within the sample due to the basically non-equilibrium nature of these materials. The present results indicate that satisfactory electrodes for noise measurements are available for superionic conductors. It is possible to observe bulk conductivity fluctuations as well as contact noise.

This research program is supported by the Office of Naval Research; Steven W. Smith carried out the experimental measurements.

SPACE-TIME CORRELATION PROPERTIES OF THE MAGNETIZATION NOISE AND MAGNETIC LOSSES

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The magnetization process in ferromagnetic materials shows an intrinsic stochastic character. This is clearly put in evidence by Barkhausen noise experiments and leads to describe the material magnetization as a random sequence of strongly correlated elementary magnetization changes, each corresponding to a sudden and localized displacement of a Bloch wall segment separating different magnetic domains.

The correlation properties of the elementary magnetization jumps have been widely investigated in the time domain, in terms of the Barkhausen noise power spectrum /1/, while space-time correlation effects have been mainly analysed only for what concerns the longitudinal propagation of the magnetic flux in the magnetization direction, usually characterized in terms of the Barkhausen noise longitudinal cross-spectrum /2/. There is no doubt however that also transverse correlation effects in the sample cross-section play an essential role in determining the magnetic behaviour of the material /3/.

The space-time behaviour of the magnetization rate $\dot{I}(\vec{r},t)$ in a given cross-section can be characterized, from a statistical point of view, by its power spectrum $\Phi_{\dot{I}}(\vec{k},\omega)$, which can be considered as a generalization of the conventional Barkhausen noise power spectrum $\Phi_B(\omega)$ (actually $\Phi_B(\omega) \equiv \Phi_{\dot{I}}(\vec{k}=0,\omega)$). $\Phi_{\dot{I}}(\vec{k},\omega)$ is expected to be directly involved in all problems where transverse correlation effects play an essential role. This is the case, for instance, when

the problem of calculating the area of the hysteresis cycle, that is the magnetic loss, is considered. Actually, the loss originates from the decay through the Joule effect of the eddy currents induced in the material by the magnetization changes, and basically depends on how the eddy current patterns produced by the single elementary magnetization jumps superpose, in space and time, in a given cross-section. The general dependence of the loss P on the magnetization rate $\dot{I}$ can be derived directly from Maxwell equations. The random character of $\dot{I}(\vec{r}, t)$ with respect to both $\vec{r}$ and t is conveniently dealt with in the Fourier space $(\vec{k},\omega)$, leading to the general loss expression

$$P = \sigma \frac{4}{S} \sum_{\vec{k}} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{|\vec{k}|^2}{|\vec{k}|^4 + (\omega\sigma\mu)^2} \Phi_{\dot{I}}(\vec{k},\omega) \quad ,$$

where S represents the sample cross-section, while σ and μ are the electrical resistivity and the reversible permeability of the material.

$\Phi_{\dot{I}}(\vec{k},\omega)$ can be explicitely calculated in the important case where the magnetization process is described as a Markov process, leading to a general characterization of transverse correlation effects and of magnetic losses in terms of the basic physical quantities describing the microscopic dynamics of the magnetization process.

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NOISE OF DIELECTRIC MATERIALS

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Our experiments carried out on samples of polyethylene terephtalate and softened polyvinylchloride showed that in the noise spectral density vs. voltage plot appears an hystereresis effect.

This is supported by the shape of the noise spectral density S_i vs. voltage U plot (Fig.1). When the voltage growth (the slope of which is about 10 V/s) is stopped (point A) the noise spectral density drops suddenly to a lower value (point B). Reversing the slope of the ramp voltage makes the spectral density drop to zero (point C) and then rise again to a value more than one order of magnitude

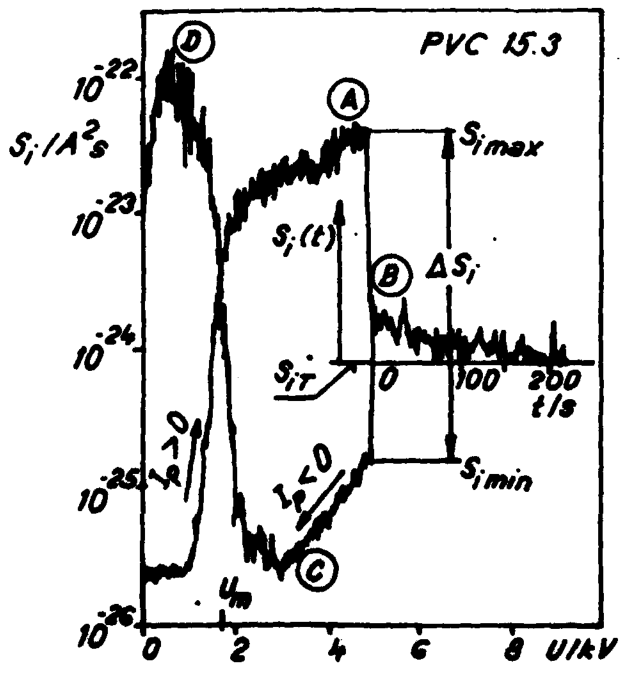

Fig. 1

higher (point D). To explain this phenomenon we assume that the dipole arrays polarization is frozen at a voltage corresponding to the voltage U_m and is released gradually between the voltages U_C and U_D .

At the point B the dielectric is in a steady electric field and the spectral density is proportional to the square of the conductivity current I_c . Decreasing the total current $I = I_c - I_p$ makes the spectral density decrease, so that the noise components due to the conductivity and polarization current are not independent.

At higher voltages than U_m the noise current exhibits sharp bursts. Rather than to micro-breakdown we attribute these bursts to abrupt changes of the orientation of the dipole arrays (quasi-domains) which are induced by the applied electric field.

The spectral density vs. frequency plot at the point D is of the generation-recombination type while at the point A the noise is of the 1/f type.

L1

Noise Analysis of laser light scattered by Nematic Liquid Crystals.

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By using the technique of optical beat spectroscopy involving the measurement of the spectral noise power of scattered light we can obtain direct information about the dynamics of single crystalline nematics, in particular the viscoelastic ratios[1]. Lorentzian line broadening is observed, from which the relaxation times can be determined. These times are related to distortions of the director pattern which are due to orientation fluctuations of the elongated molecules[2].
Except for special and restricted optical configurations the expression for the noise intensity of the scattered light is a sum of three Lorentzians. These Lorentzians have halfbandwidths which are linear functions of the inverse relaxation times. These times are connected with two uncorrelated distortion modes of the nematic[3].
The problem now is to determine the two relaxation times seperately, which may differ only slightly in magnitude.
The Lorentzians, however, occur in the expression for the noise intensity with weighting factors associated with the optical configuration, *c.f.* the scattering angle. By varying the scattering angle the weights are changed[4]. Measuring the spectral noise power for a sufficient large set of scattering angles we are able to single out the two relaxation times, with the help of computer analysis.

Additional information about the statistical properties of director fluctuations in nematic liquid crystals can be obtained by studying the statistics of scattered laser light. In particular, by combining measurements of the autocorrelation function of the intensity of scattered light with measurements of the probability distribution and time-interval statistics of scattered photons, one can ascertain to what extent director fluctuations behave as a Gaussian-Lorentz process[5]. Experimental data on the statistical properties of director fluctuations in some simple nematogens close to the isotropic-nematic transition will be presented.

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Noise in organic semiconductors

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Tetracyanoquinodimethane (TCNQ) forms crystalline organic conductors with morpholinium derivatives. The organic conductors often show several phases i.e. an insulating, a semi -conducting and a metallic phase. (1). They are quasi-onedimensional conducting i.e. the conductivity is anisotropic. The electrons (and holes) can move more freely along the stacks of TCNQ molecules than in other directions. Interest in the crystalline organic semiconductor is stimulated by the occurence of typical one dimensional effects and high conductivity (2).
It seemed worthwhile to study the properties of these materials in order to obtain more insight in the conduction processes. We have studied noise phenomena in semi-conducting TCNQ salts as a function of temperature. In this regime of operating the morpholinium derivative, for example methylbutylmorpholinium, acts as a donor of electrons and the TCNQ as an acceptor. We have found 1/f noise and generation-recombination noise. The latter is of great importance because it provides an unique method for determining the number of charge-carriers (3), whereas in these quasi-onedimensional conductors the interpretation of Hall-effect data is ambiguous. Results of the low frequency (f <1MHz) generation-recombination noise levels $S_I(0)$ and the relaxation times as a funtion of temperature are discussed.

L1

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FRIDAY AFTERNOON

ROOM A

NOISE IN SUBMICRON DEVICES

(Invited paper)

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The reduction of the size of semiconductor devices gives rise to specific problems, non encountered in "long" devices, due to physical mechanisms involved when fast transient regimes ($\lesssim 10^{-12}$ s) and/or small dimensions ($\lesssim$ 1 µm) are considered. The effect of these mechanisms (overshoot velocity, ballistic transport, etc...) have been investigated since a few years on first order characteristics. Moreover, noise properties are also modified: although corresponding studies have not yet been performed extensively till now, many questions of great physical interest arise, which also may have important consequences in VLSI devices.

In this paper, the most important features involved, in scaling down the size of devices, are reviewed:

- Parameters of minor importance in long devices can have significant or even preeminent effects in short devices.
- The relative effects of the various noise sources may not be the same for long and short devices made of the same material (decreasing importance of the diffusion noise, effect of localized defects, carrier-carrier scattering due to higher carrier densities, etc...)
- Non stationary effects should be taken into account (diffusion for example)
- The noise sources at two neighbouring points cannot be considered as being uncorrelated
- Three dimensional effects occur even in one dimensional devices

L1

- What is the effect of the finite time duration of the collisions?
- Some very short devices may behave as discrete systems and not continuous ones, with a great sensitivity *to the microscopic* structure (porus in membranes, inversion layers, superlattices,...)
- The statistics of very low populations (< 30) is no more gaussian.

Most ot these questions have not yet receive any answer till now.

HOT CARRIERS AND SUBMICRON DEVICES

Ll

MICROWAVE ELECTRIC AND MAGNETIC NOISE IN MAGNETIC SEMICONDUCTORS IN HIGH ELECTRIC FIELD

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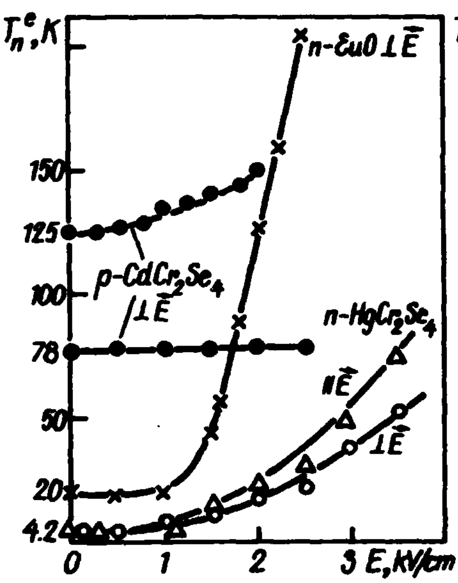
Magnetic noise (fluctuation of magnetization) in addition to the electric one is characteristic in magnetic semiconductors. Microwave electric as well magnetic noise, which rezults from thermal motion of electrons and magnetic atoms may be used as the diagnostic tool for the electron and magnon heating determination. Conductivity and magnetization dependence on electric field in EuO and $CdCr_2Se_4$ indicates the possibility of electron heating as well as magnon exitation in magnetic semiconductors in high electric field [1] .

There the experimental results of electric and magnetic noise in microwave range (1o GHz) in EuO, $CdCr_2Se_4$ and $HgCr_2Se_4$ below Curie temperature in high electric field is presented.

The considerable increase of the electric noise temperature T_n^e in EuO and $HgCr_2Se_4$ in high electric field E is observed (Fig. 1). In $CdCr_2Se_4$ the T_n^e depends on the electric field only at lattice temperatures exceeding 100 K. These data show that the current carriers are heated by the high electric field in magnetic semiconductors.

It was found that in $HgCr_2Se_4$ (Fig. 2) the electric field

increases the magnetic noise temperature T_n^M ($T_n^M = \dfrac{\langle \delta M^2 \rangle_\omega}{4k\omega\chi''}$, where $\langle \delta M^2 \rangle_\omega$ is the spectral density of the magnetization fluctuations, χ'' - imaginary part of magnetic susceptibility, k is the Boltzmann constant, ω - angular frequency). The results of the magnetic noise temperature measurements may be explained assuming that drifting electrons stimulate magnons with the definite momentum and energy.



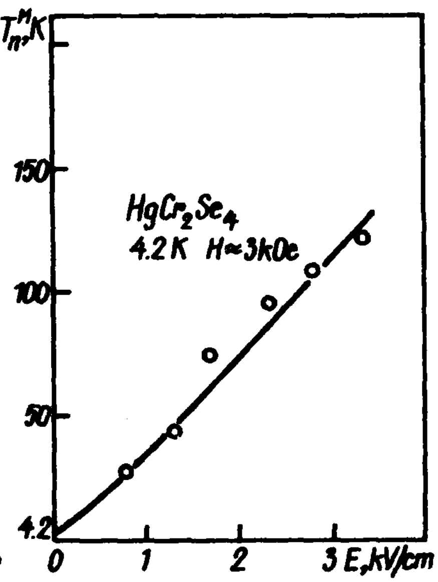


Fig. 1. T_n^e v.s. E
∥ - parallel to $\vec{E}$
⊥ - perpendicular to $\vec{E}$

Fig. 2. T_n^M v.s. E

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is that of a two level system [2] and the corresponding noise spectrum is [4]

$$[S_I(\omega)]_{int} = \left(2e^2AF^2/L\right)(\mu_1 - \mu_2)^2 \frac{n_1n_2}{(n_1 + n_2)} \frac{\tau_0}{(1 + \omega^2\tau_0{}^2)} \qquad (2)$$

Here the electron temperatures are constant, hence, μ is the chordal mobility and $1/\tau_0 = \Gamma_{n12} + \Gamma_{n21}$ where Γ_{nij} is the rate of change of the distribution function due to intervalley scattering.

Results for GaAs show that the low frequency noise (< 1 GHz) is dominated by the intervalley components except when almost all the electrons are in one valley. The noise power rises dramatically in the negative differential resistance (ndr) region. The peak in high frequency noise (> 10^{12} Hz) in the ndr region is attributed to changes in electron temperature and conductivity. Unlike silicon there is no maxima in the noise spectrum. This and other differences between noise in silicon and GaAs are discussed. A comparison with the noise obtained by applying Nyquist's formula to each valley will be made. The effect of finite collision duration will be studied.

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GENERATION-RECOMBINATION NOISE IN n-Si AT 77K

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Previous results (1) showed in n-Si below 110K, at low frequency, noise temperatures T_n (E, ν =0) too high to be explained only by diffusion noise.

In this paper we give experimental results $T_n - T_o = f(E,\nu)$. At a given electric field, the curve $T_n - T_o = f(\nu)$ at 77K, shows a cutoff frequency around 3GHz (fig.1). This phenomena can be explained by the fact that all the carriers are not thermally ionised at this temperature and may be ionised by impact ionisation or Pool-Frenckel effect. This is GR noise of hot carriers. From these results we are able to get, the number of ionised carriers, the mobility of carriers, and the diffusion coefficient, versus the electric field. For getting these quantities, we fit the three parameters of the theoretical noise (sum of the diffusion and of the GR noises) to the experimental results. No assumption is needed as concerning the detailed microscopic nature of the noise.

(1) A. Van Der Ziel, R. Jindal, S.K. Kim, H. Park and JP. Nougier.
S.S.E. Vol. 22 pp. 177-179

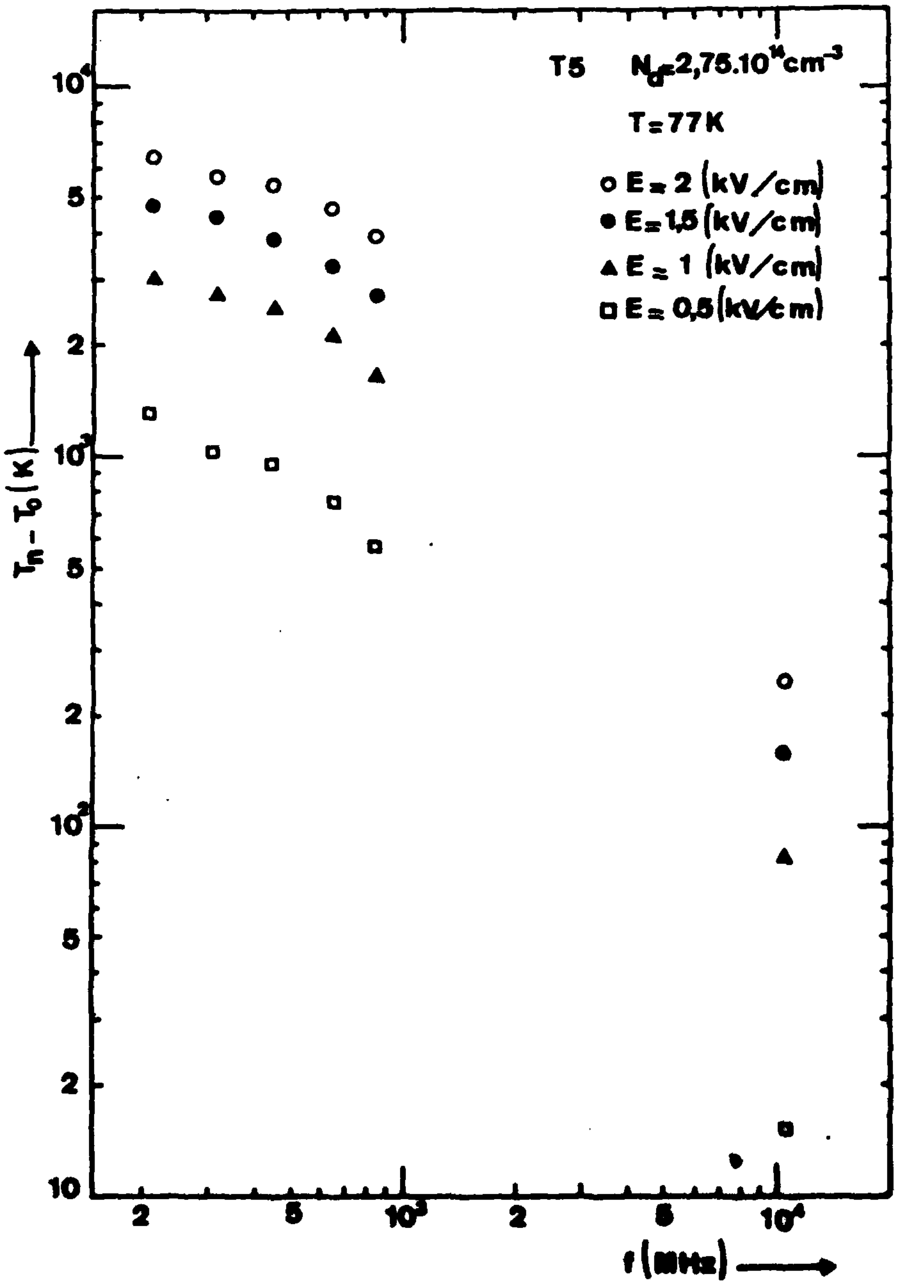
T5 N_d=2,75.10^{14}cm^{-3}
T=77K
E= 2 (kV/cm)
E=1,5 (kV/cm)
E= 1 (kV/cm)
E= 0,5 (kV/cm)
$T_n - T_0$ (K)
f (MHz)
10^4
5
2
10^3
5
2
10^2
5
2
10
2
5
10^3
2
5
10^4

Fig.: 1

L1

HOT CARRIERS NOISE IN n-TYPE InP

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The interest of high mobility semiconductors is now proved particulary to realize high frequency devices.

Indium phosphide seems to be a good semiconductor for such devices. Therefore it was interesting to study this material to obtain noise and transport coefficients. We used $n^+ n n^+$ mesa diodes. The active n layer had a thickness of 5 um and a doping of about 2×10^{15} cm^{-3}. To study these devices in hot electron regime it was necessary to know the electric field map to be sure that the field was uniform. A simulation showed that electric field was uniform until 6 kV/cm. So it was possible to measure the noise temperature versus the electric field (Fig. 1). The study of this noise as a function of frequency showed, at room temperature a cut off frequency of about 4 MHz due to G.R. noise. We fitted the experimental datas with the theoretical curve using three parameters, the number of ionized carriers, the cut off frequency, and the diffusion coefficient, and we obtained the value of these parameters versus electric field. We found that the average number of ionized carriers was independent of the electric field intensity and close to one. This fact suggests the existence of a trapping level in the gap. Finally we give for the first time the experimental diffusion coefficient versus electric field.

L1

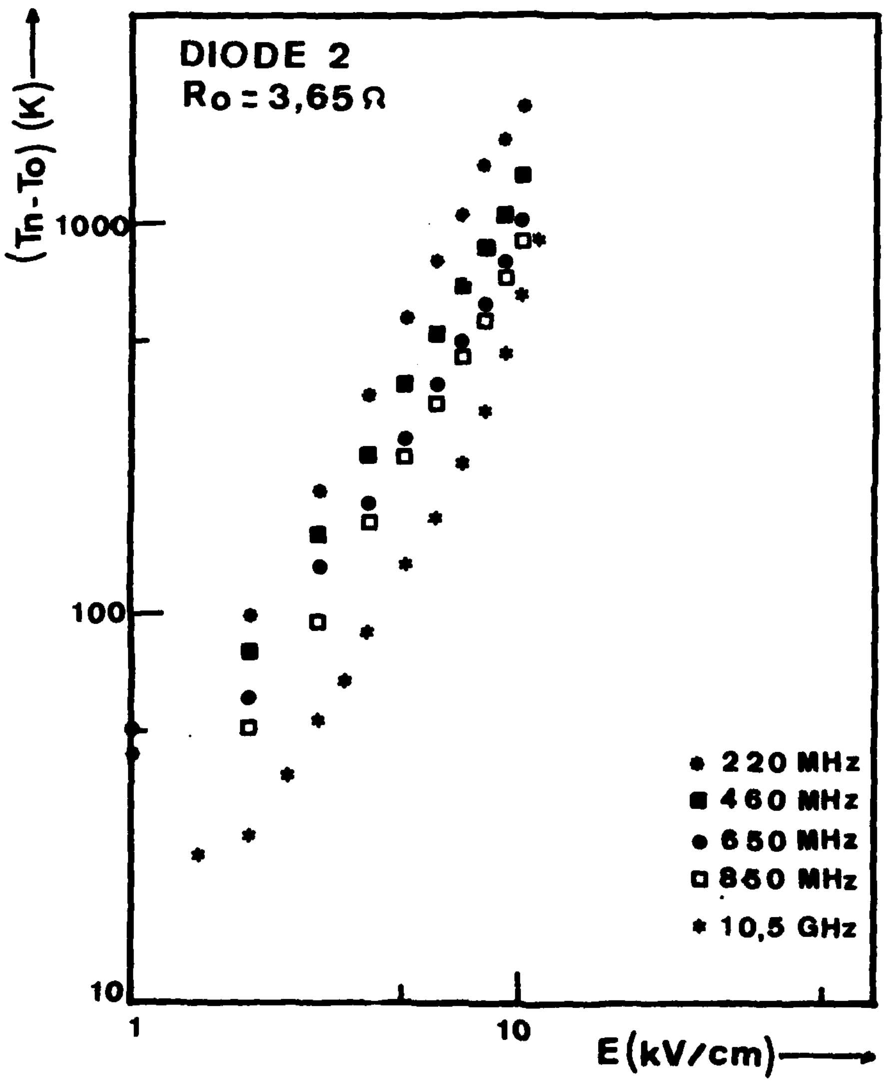
DIODE 2
Ro = 3,65 Ω
(Tn-To) (K)
1000
100
10
1
10
E(kV/cm)
220 MHz
460 MHz
650 MHz
850 MHz
10,5 GHz

fig. 1

<u>Noise in near-ballistic n^+nn^+ and n^+pn^+ gallium arsenide submicron diodes</u>. R.R. Schmidt, G. Bosman, C.M. Van Vliet, and A. van der Ziel, Department of Electrical Engineering, University of Florida, Gainesville, Florida, and L.F. Eastman and M. Hollis, School of Electrical Engineering, Cornell University, Ithaca, New York.

DC characteristics and noise measurements are reported for n^+nn^+ and n^+pn^+ near-ballistic devices, with n regions (p regions) of 0.4 μm (0.45 μm), fabricated by molecular beam epitaxy at Cornell[1]. The n^+nn^+ mesa structures have a linear DC characteristic, though the samples are near-ballistic, in accord with calculations by Holden and Debney[2]. The noise for these samples is extremely low, see the spectrum in Fig. 1. The Hooge parameter computed from these data is

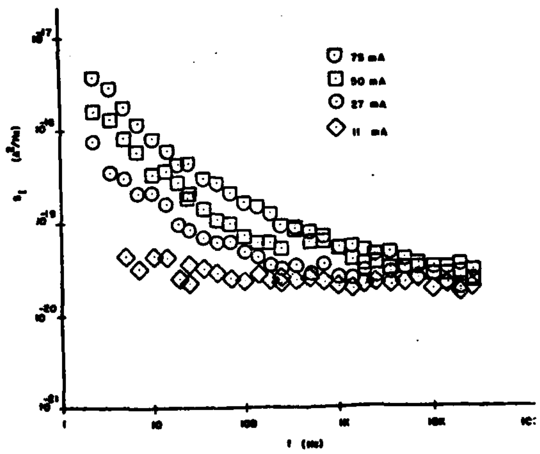

Figure 1

$\alpha_H = 2 \times 10^{-9}$. This extremely low value, compared to bulk gallium arsenide listed by Hooge et al[3] as 6×10^{-3}, indicates the near absence of electron phonon collisions. At high frequencies the noise is thermal noise of the resistance (0.75Ω) within 7%; this extremely low noise was measured with a cross-correlation technique. The DC characteristic of the n^+pn^+ devices was highly nonlinear. It is best represented in the form of I/V versus V; Fig. 2 gives the result for various temperatures.

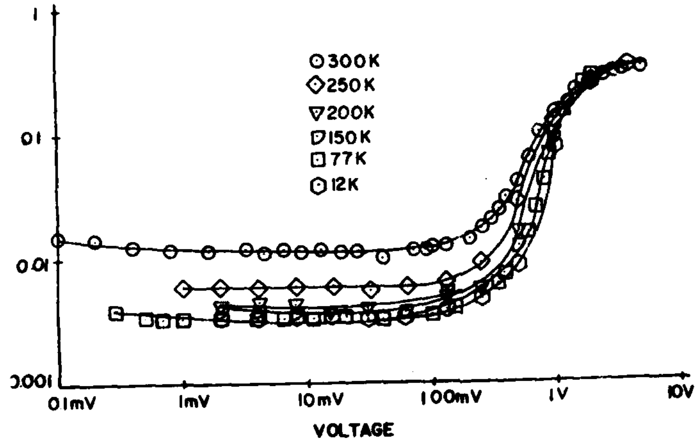

Figure 2

For low bias the current is attributed to electrons passing *through the potential* minimum, ambipolarly governed by the holes in the p region; because of the low hole mobility, the current is collision dominated for this region. For higher bias the injected electrons exceed the hole density in the p region and ballistic flow occurs; this conductance asymptote is independent of temperature. The noise measurements confirm this interpretation. At low bias the noise is very high. The Hooge parameter at 300K is $\alpha_H = 3 \times 10^{-3}$. At higher bias the noise goes no longer as the square current, but grows slower. We expect the noise to go down to the low ballistic noise of the n^+nn^+ samples for very high bias. Pulsed noise measurements to confirm this behavior are underway. Some remarks will also be made on the expected behavior of p^+pp^+ and p^+np^+ devices.

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L1

A NEW NOISE MODEL OF SUBMICROMETER DUAL GATE MESFET

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In the models available up-to now, the dual gate MESFET was considered as two single gate FET's in cascode configuration. Such models cannot provide accurate theoretical predictions, because they do not take into account two main physical effects:

- the correlations between the noise current sources in gate 1 and 2 and in the drain circuits.
- the non stationnary electron dynamics effects during the electron transit in the channel.

The model which we propose takes these effects into account. The numerical resolution of carriers transport current continuity and Poisson equations within the channel can be performed by means of a deskshop computer. The carriers transport equations used are momentum and energy relaxation equations obtained by integration of Boltzmann equation[1]

Noise is due to the carriers density fluctuations in the channel : for each section of width Δx in the channel, their spectral density is proportional to the local electronic temperature T, and it is assumed that T is only dependent on the average carrier energy [1]. The contributions of these fluctuations to the gate and drain noise currents are numerically added and correlation coefficients are evaluated. The knowledge of the noise sources allows us to evaluate the noise figure by using classical methods and taking into account the influence of parasitics elements (source and gate resistance for instance).

MAIN RESULTS

In order to prove the validity of our model, theoretical predictions are systematically compared with experimental results for several different dual gate FET's between 6 and 18 GHz. The physical behaviour of the device has been studied in details, and especially, as it is shown in figure 1, the comparative contributions of each section in the channel to the equivalent external noise current sources and the variations of the correlations coefficients with bias conditions. The noise figure dependence upon operating conditions (frequency and d.c. bias) and technological parameters (doping level, epitaxial layer thickness, gate length...) is accurately evaluated. For instance, it is clearly shown, in figure 2, that for submicrometer gate lengths, the noise figure does not strongly depend on the gate bias, as it has been previously shown for single gate FET's [1]. As it is also experimentally shown, the noise

figure can be greatly reduced, when the signal is applied on the second gate. This suggests to use a new kind of configuration to realize a controlled amplifier.

This work was supported by the D.R.E.T. under contract N° 81/330.

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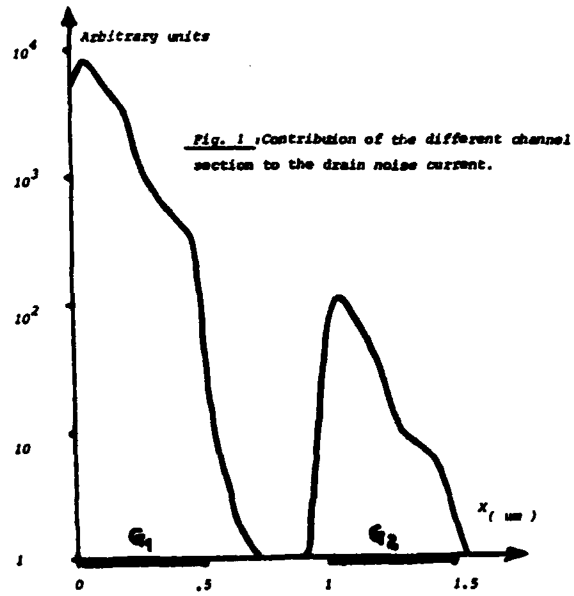

Fig. 1 :Contribution of the different channel section to the drain noise current.

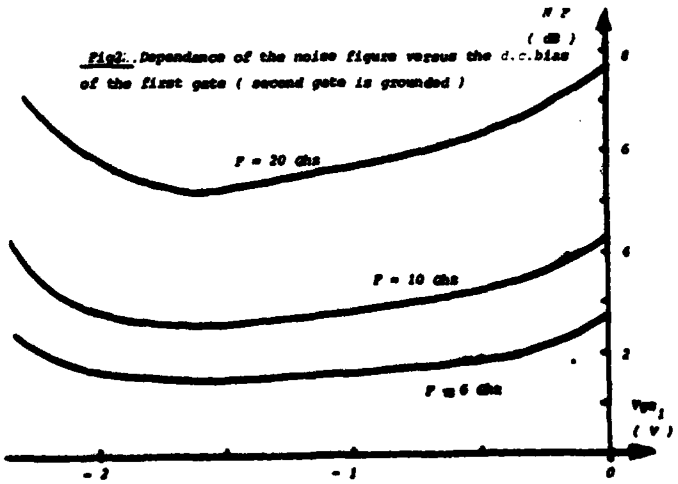

Fig2. Dependance of the noise figure versus the d.c.bias of the first gate (second gate is grounded)

L1

F R I D A Y   A F T E R N O O N

ROOM B

L1

1/f NOISE IN DIODES

[redacted]

L1

Low frequency noise in $Al_xGa_{1-x}As$ - GaAs two dimensional electron gas devices and its correlation to deep levels

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$Al_xGa_{1-x}As$ - GaAs - heterostructures grown by molecular beam epitaxy are the most important materials for very high-speed two dimensional electron gas devices. Electrons are transferred from the n-doped AlGaAs into the undoped GaAs and form a quasi two-dimensional gas at the interface. Since ionized shallow impurities are absent in the GaAs layer a very high mobility especially at lower temperatures results, which explains the high speed of the devices and promises lower microwave noise.

Deep impurities reduce carrier concentration, degrade transport properties and increase noise. Though several investigations of deep levels at GaAs-GaAs-homostructures have been reported /1/, little is known about AlGaAs-GaAs heterostructures.

A powerful tool for characterizing deep levels (activation energy, capture coefficient, concentration) is the measurement of generation - recombination (g-r) noise at low

frequencies. Therefore such measurements were carried out and a set of deep levels was detected.

The heterojunctions had the following structures:

type I

22 nm GaAs undoped (p^-)
60 nm $Al_{0.22}Ga_{0.78}As$ (n) (Si-doping $1x10^{18}cm^{-3}$)
GaAs undoped (p^-) s.i. - substrate

type II

20 nm GaAs undoped (p^-)
70 nm $Al_{0.3}Ga_{0.7}As$ (n) (Si-doping $6x10^{17}cm^{-3}$)
6 nm $Al_xGa_{1-x}As$ undoped
1.1 μm GaAs undoped (p^-) s.i. - substrate

The test devices had two ohmic contacts with 6 - 60 μm separation. Low-frequency measurements in the range 1Hz to 25KHz were carried out by a computer-controlled spectrum-analyser with dc-current applied to the device. To determine the deep level parameters the sample temperature had to be varied. This was done within a range of 20K to 400K. The measured data were processed and evaluated by a computer program /2/. The results will be discussed and compared with data obtained by other methods and other authors.

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1/f NOISE IN P⁺NN⁺ DEVICES. INFLUENCE OF A MAGNETIC FIELD

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We present and analyse experimental results on the 1/f noise of double injecting structures (p^+nn^+ "long" diodes, see fig.1, working in the "semiconductor regime"), together with the influence of a magnetic field on the noise level.

Experiments have been performed on devices made with SOS (Silicon On Sapphire) or germanium technologies. Integrated SOS diodes (*) were 0.6μm thick, with different lengths (10 to 50μm), widths (50 to 200μm) and dopings ($5.10^{15}cm^{-3}$ to $10^{17}cm^{-3}$) ; Ge structures (dimensions ∿ mm) were processed from low-doped ingot. If the length is greater than the carrier diffusion length, the mean current is essentially controlled by a bulk effect ; such long p^+nn^+ (or p^+in^+) devices are often named "magnetodiodes" [1] because their forward current-voltage characteristics ($I \propto V^2$) are very sensitive to a transverse magnetic field B. In this respect, the noise appears as a practical limitation of their sensitivity.

Several properties of the noise power spectral density are illustrated in figs. 2 to 4. Quite generally, we observe 1/f noise below 10 kHz. At B = 0, the noise increases like I^2 ; fig. 2 also shows that the noise strongly depends on the diode length. Besides,the noise is raised in low-doped or narrower structures. Thus the noise variations qualitatively agree with the modifications of the device resistance. The magnetic field influence also corresponds to such an effect : in SOS structures (fig.3), for a constant current, the voltage is increased by 6 % and the noise by approximately 50 % when the magnetic field B is reversed. In Ge magnetodiodes (fig.4), noise variations are much more important due to their highest sensitivity to B. Moreover the noise can be lowered by the magnetic field. This behaviour is quite different from the case of noise in the pure magnetoconcentration effect (no injection) previously reported [2] ; there,the 1/f noise under a magnetic field was shown to result from surface recombination fluctuations.

(*) Supplied by LETI/CEN Grenoble

The 1/f noise of magnetodiodes appears to be more tightly related to bulk effects. Several possible noise sources will be discussed, including the influence of contact noise and of the non-uniform carrier distribution.

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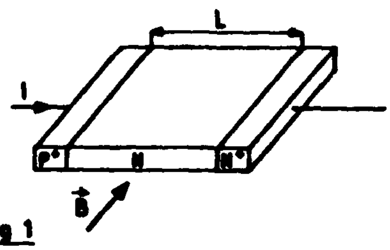

Fig 1

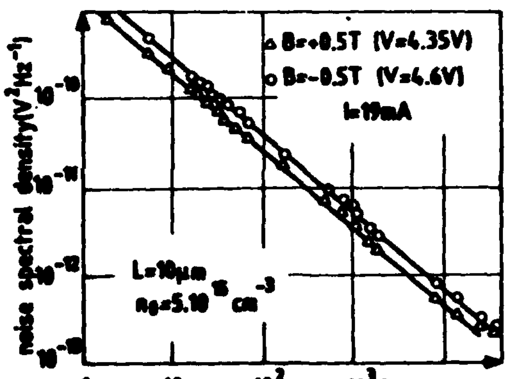

Fig 3

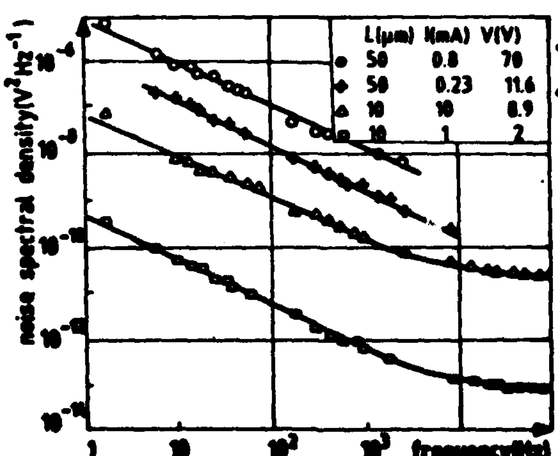

Fig 2

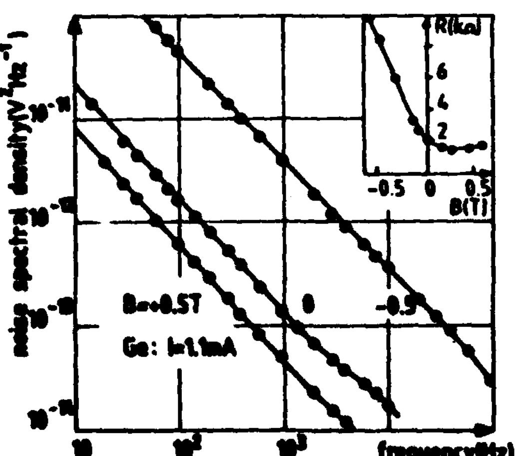

Fig 4

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1/f NOISE IN RESISTORS

1/f NOISE MAGNITUDE IN FINE-GRAINED ALUMINIUM FILMS

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The paper deals with the analysis of influence exerted on the magnitude of 1/f noise by the size of grains that make up thin continuous aluminium films. 170-nm thick polycrystalline samples evaporated on glass substrates have been investigated. The grain sizes l were determined by means of accidental secants on photoes taken in a transmission electron microscope. The values of parameter α defined as [1]

$$\alpha = S_V(f) N_c f / V^2$$

was obtained through the measurements of $S_V(f)$ (where S_V is the spectral density of voltage fluctuations, V is the

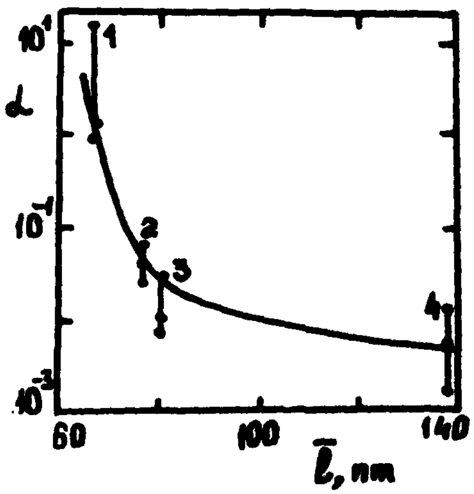

Fig.1

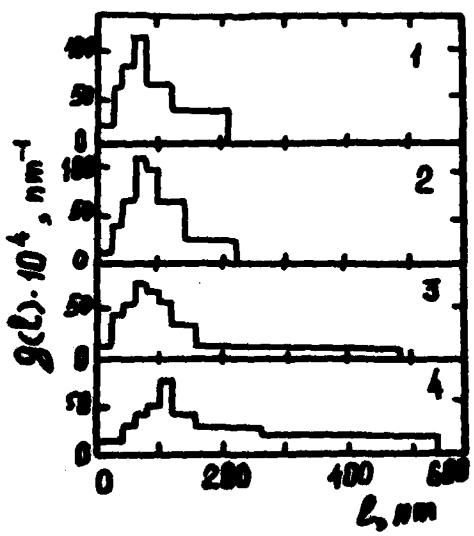

Fig.2

dc voltage across the sample, f - the frequency of observations, N_c - the total number of charge carriers). The parameter α values approach Hooge constant $\alpha_s = 2 \cdot 10^{-3}$ in samples considered coarse-grained (their average size being over 100 nm). With the twofold dimishing of average grain size the noise magnitude increased by three orders (Fig.1). Histograms of grain size distributions (Fig.2) indicated that the rise in noise magnitude correlated well with the increased proportion of fine grains ($l \leq 50$ nm). This fact was interpreted as an evidence of fluctuations in structural defects scattering resistivity component. A model has been elaborated for 1/f noise due to conductance modulation by bulk vacancy concentration fluctuations; 1/f spectrum is to be obtained in an usual way as a superposition of Lorentzian spectra [2]. Temperature dependence of spectral density in metals and noise magnitude decrease with annealing procedure [3,4] conforms to the above model.

This work has been done in collaboration with G.P. Zhigal'skiy.

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ZERO-POINT LATTICE VIBRATIONS IN 1/f NOISE IN METALS

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Temperature dependence of spectral density S of 1/f noise in metal films corresponds to Arrhenius law $\ln S \sim$ $\sim -1/T$ within the range of $200 \div 400$K and tends to flattening at further lowering of temperature [1,2]. In conformity with the other experimental data [1-3] activation character of temperature dependence makes it possible to account for the origin of 1/f noise in metals by the dynamics of crystal structure defects. The present report is concerned with the causes of spectral density deviation from Arrhenius straight line at low temperature.

The origin of the noise is assumed to be affected by certain processes, whose intensity is proportional to the energy of lattice vibrations. When temperature lowers, the energy decreases and so does the noise power. At temperature approaching zero zero-point vibrations remain and temperature dependence flattens.

The flattening shows that the origin of 1/f noise is greatly dependent on transitions that have the same or next to the same energy in initial and final states; this also rules out mechanisms connected with fluctuation transition to a high-lying level.

It can be concluded [4,5] that in the case of vacancy migration deviations from Arrhenius law are to be expected at temperatures estimated by $T \approx (\frac{1}{3} \div 1) T_D$ where T_D is

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Debye temperature. Whereas the flattening takes place at $T \approx (0.1 \div \frac{3}{8}) T_D$ in the case of dislocation movement [6]. Experimental dependence of 1/f noise spectral density in Au, Ag, Cu [1] and Al [2] deviates from Arrhenius straight line at $T \approx (0.6 \div 1.2) T_D$. Thus, the low temperatures features seem to be an evidence of that the noise is caused here by point defects rather than dislocations.

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